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THE IMPACT OF BUILDING ORIENTATION ON
RESIDENTIAL HEATING AND COOLING

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DISCLAIMER

THE IMPACT OF BUILDING ORIENTATION ON RESIDENTIAL HEATING AND COOLING*

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ABSTRACT

Heating and cooling loads have been calculated for a prototype residential building at different orientations, using a development version of the building energy analysis computer program BLAST.** The study was carried out for 25 climates in the United States. It was found that in all climates, when the more extensively glazed exposure is oriented to south, total loads are significantly lower than those in the same building oriented east or west. North orientation also produces lower total loads than east or west orientations in the southern two-thirds of the U.S., and roughly equivalent loads in the northern third. Total loads are higher for north than south orientation except in extreme southern latitudes of the U. S. (those areas with dominant cooling loads). Variation of peak loads in response to orientation and sensitivity of results to (1) total window area and its distribution, (2) size of window overhangs, and (3) level of thermal mass are reported.

1. INTRODUCTION

Long before a building design is actually begun, decisions are made which significantly affect the eventual orientation of a building. Planners making the original street layout of an area will determine whether most buildings will be oriented along one axis of the site or along the axis perpendicular to it. These decisions are based on the location of connecting roads, drainage patterns, utility line access,

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** BLAST (Building Loads Analysis and System Thermodynamics) is trademarked by the Construction Engineering Research Laboratory, U.S. Department of the Army, Champaign, Illinois.

view, and other factors; in the past, energy has typically not been considered an issue in these decisions.

Typically, streets are laid out on a grid or some modification of a grid, with most streets running in two perpendicular directions. Blocks are commonly of such a shape that streets run predominantly in one of those two directions. Residences, regardless of their precise shape, tend to have the majority of their windows facing either directly toward or directly away from the street. Past studies of total energy consumption in residential buildings [1-5] have shown a strong relationship between thermal performance and glazing distribution. It is suspected therefore that building orientation and its relationship to site planning and building design can have substantial influence on the end-use energy consumption of a building.

A systematic investigation of this effect was undertaken, using BLAST to simulate a prototype residential building in a variety of U.S. climates. In order to convey to municipal officials, planners, and architects the importance of early decisions on zoning, street layout, site planning, and building concept, estimates of the likely impact of residence orientation on heating and cooling loads have been presented in simple maps and tables. In order to examine the extent to which prototype design assumptions determine a building's response to orientation changes, the prototype design was altered and simulated in representative climates. The design parameters which were varied in these sensitivity studies were glazing area, shading design, and amount of thermal storage mass included in the structure.

Properly orienting a residence is a highly effective way to lower energy use and, if planned early, may be simple and inexpensive to accomplish. Furthermore, proper orientation in the first place can create potential for additional savings from more sophisticated passive solar techniques. However, there are many methods available to improve performance of windows in any orientation; shading, movable insulation, and special glass or glass coatings can each be used to good effect in many situations.

2. METHODOLOGY

2.1. Prototype Building Description

The prototype residence analyzed in this study has been used for a variety of parametric studies [1,6-9] prior to this investigation. A detailed description of the architecture and occupancy of the base building used in these analyses is presented in Appendix 1; its salient features are summarized below:

2.1.1. Architecture

While it is impossible to define a "typical" residence in the United States, the structure analyzed here is representative of a broad range of designs. The 1176 ft^2 building has a rectangular floor plan (see Fig. A1-1). The glazing area of 176 ft^2 is 15% of the floor area, which is typical of much construction in the U. S. Double-pane glass is used for all windows. The glazing is unevenly distributed over the four exposures; 132 ft^2 appears on one of the long facades while the remainder (44 ft^2) is allocated to the opposite side of the structure in order to provide for cross-ventilation and view. (In this report, the building is said to be "facing" in the direction of the larger area of glass. See Fig. 1). The original building configuration, with most glazing on one long wall and the rest on the other long wall, was selected on the basis of "passive design optimization" studies reported in a previous paper [1]. This glazing arrangement was retained in the current study for two reasons: (1) having a preponderance of glazing on one side of the building should produce a clear indication of the effect of orientation on energy consumption, since variations in solar gain through glazing is the dominant effect associated with reorienting the building; and (2) having most or all glazing on opposite sides of the building will give a clear indication of the potential importance of street layout, since there is a strong tendency to place most glazing facing directly toward or directly away from the street.* All windows are shaded by a 1.5 foot overhang. (For other studies [1,6,7] the building was assumed to face south, and was therefore provided with additional shading.)

The base building contains thermal mass in a concrete floor slab which is insulated from the ground, and in concrete partition walls which define three occupied zones. Half the floor is covered with carpet. Insulation levels in walls and ceiling are expected to be standard practice in the near future.

2.1.2. Building Use and Control

The building is assumed to be occupied and to have typical levels of internal heat generated by equipment and lighting; auxiliary heating and cooling equipment is controlled entirely by air temperature thermostats. The heating and cooling systems are assumed to have sufficient capacity to meet the loads in the structure for all hours of the year. The cooling thermostat is set at 78°F for the entire simulation period while the heating thermostat is at 70°F during daytime hours and setback to 60°F from 11:00 p.m. to 7:00 a.m.

For this study, the building was assumed to have a forced ventilation cooling system to prevent overheating during the heating season and reduce cooling loads during the summer. The control strategy for the

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* Windows facing the street also tend to have greater solar exposure (with consequently greater energy significance) because of additional open space which the street creates. In the simulations, a flat site is assumed, both for simplicity and to give a clear indication of the potential importance of orientation. Also, all glazing is facing directly toward or away from the street, for the same reason. In looking at a large population of typical residences, the results will be less pronounced than those presented here.

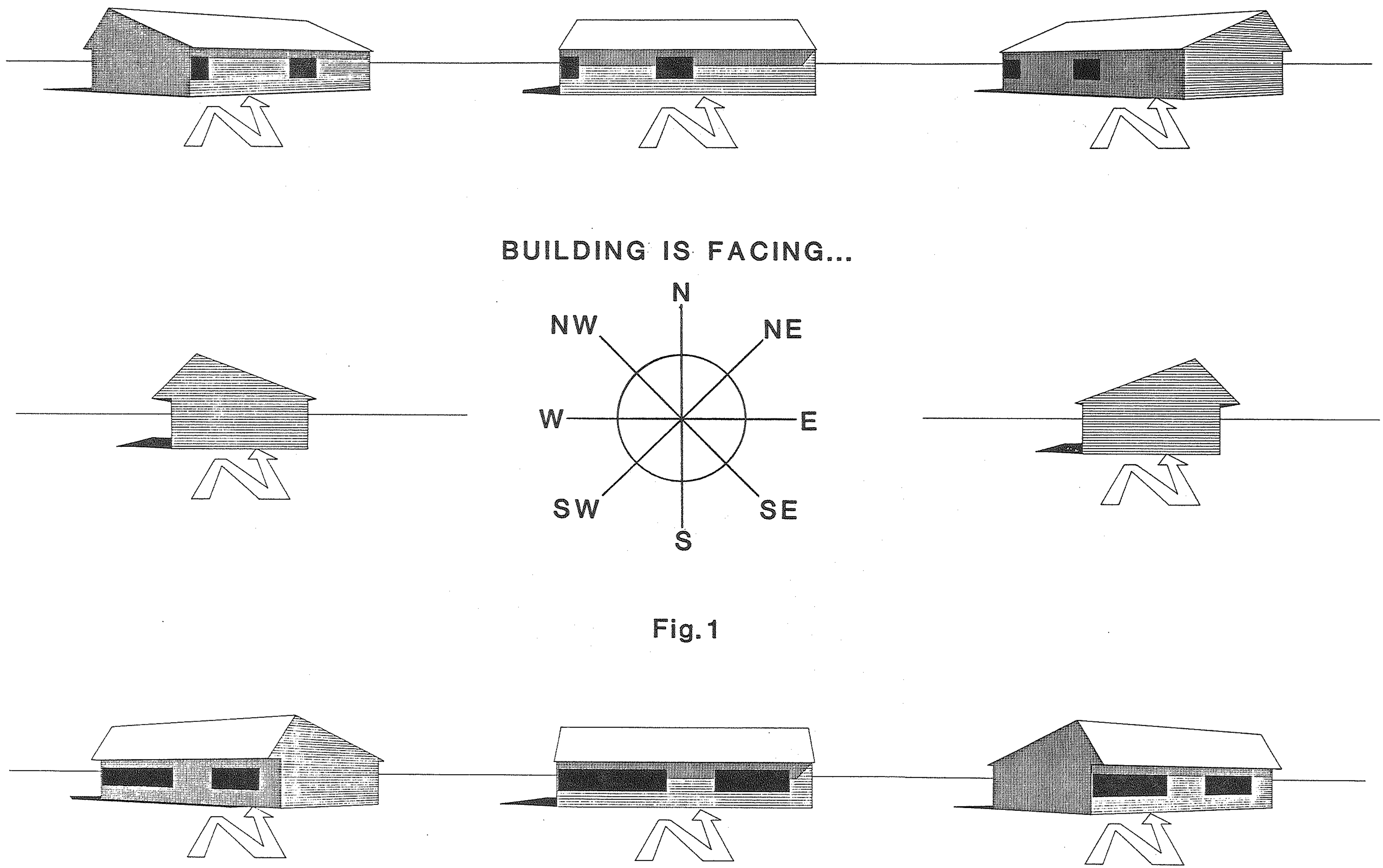

Fig.1

heating season consisted of ventilating the space only when an occasional cooling load occurred and when outside temperature permitted immediate ventilation cooling. Under these conditions, the ventilation system maintained indoor air temperature just below the auxiliary cooling system thermostat setting. During the cooling season, the building was ventilated whenever it was possible to lower inside temperature by such a strategy. If the heating set point (70^{o}F) was reached, ventilation was shut off. The period during which this precooling strategy was employed was determined by examining monthly heating and cooling loads from baseline simulations.

2.1.3. Parametric Sensitivity

The base building is architecturally identical for all climates investigated in this study. As described in Section 3, the base building description was modified for some simulations in order to examine sensitivity of loads to certain parameters important to the orientation issue. Three separate building modifications were employed:

- the 1.5 ft. overhang was replaced by one of 3.5 ft. over the major window area;
- concrete partition walls were replaced with more conventional 2 x 4 stud walls faced with gypsum board; and
- the major window area was increased from 132 to 156 ft^2.

As noted above, a more complete description of the building is given in Appendix 1.

2.2. BLAST

The building energy analyses reported here utilized a developmental version of the public domain program BLAST 3.0. Several features of the program are especially important:

- Heating and cooling loads are calculated on an hourly basis.
- Analysis of solar gain through windows and opaque surfaces is performed in considerable detail using beam, diffuse, and ground-reflected solar radiation data.
- Thermal response factors are used to account for the effect of structural mass in storing heat and in delaying conduction of heat through the building envelope.
- Users can define thermostat control strategies, including night setbacks. Air temperature is allowed to float between thermostat setpoints during the thermal load calculation.
- The program utilizes an iterative thermal balance technique which allows simultaneous simulation of adjacent zones while properly accounting for dynamic effects of thermal storage in, and conductive heat transfer through, constructions defining individual

zones.

- In the LOADS portion of BLAST, from which all results in this report are taken, no accounting is made of latent loads. Orientation should have negligible effect on latent loads, but one should keep in mind that when cooling loads are compared to heating loads only the sensible component of the cooling load is being used. The effect of latent loads is most pronounced in the Southeast and Gulf Coast regions.

Other important features and characteristics of BLAST 3.0 are described in Appendix 2.

2.3. Typical Meteorological Year (TMY) Weather Data

Weather data used in loads calculations were taken from TMY tapes for 25 sites located across the United States (Fig. 1a). The hourly data were used to drive annual BLAST simulations of the prototype residence. TMY weather tapes are produced by the National Oceanic and Atmospheric Administration.* They are aggregates of statistically selected "typical" months from the long-term SOLMET data base. TMY data provide sufficient detail and a consistent format for reliable parametric studies. Of particular importance to orientation issues is the heavy weighting given to measured solar radiation in selection of "typical" months.

3. RESULTS

For 25 climates and for buildings facing in the four cardinal directions, heating and cooling loads have been calculated for the prototype building. For the sake of simplicity heating and cooling loads are summed for each case and resulting total loads are compared.** Combining heating and cooling loads provides a single index which gives a

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* TMY tapes and documentation are available from N.O.A.A., Asheville, North Carolina.

** If one assumes that residential air conditioning has an average COP of 2, and electricity generation and transmission efficiency is .35, an overall cooling efficiency of .7 is achieved. If gas or oil is used for heating, with an efficiency of .7, then the cost of meeting the two types of loads is similar, both in terms of dollars and primary fuel use.

Clearly, this is a convenient generalization which greatly simplifies analysis, but does not always hold. Significant divergence from this simple assumption is observed in any area of dominant cooling loads where electric heating and/or evaporative cooling are widespread. In such an instance, heating would be much more important relative to cooling, in terms of cost or primary fuel use per Btu of load. For this reason, we have included heating and cooling load changes separately in Tables Ia-Ic.

25 Locations Analyzed

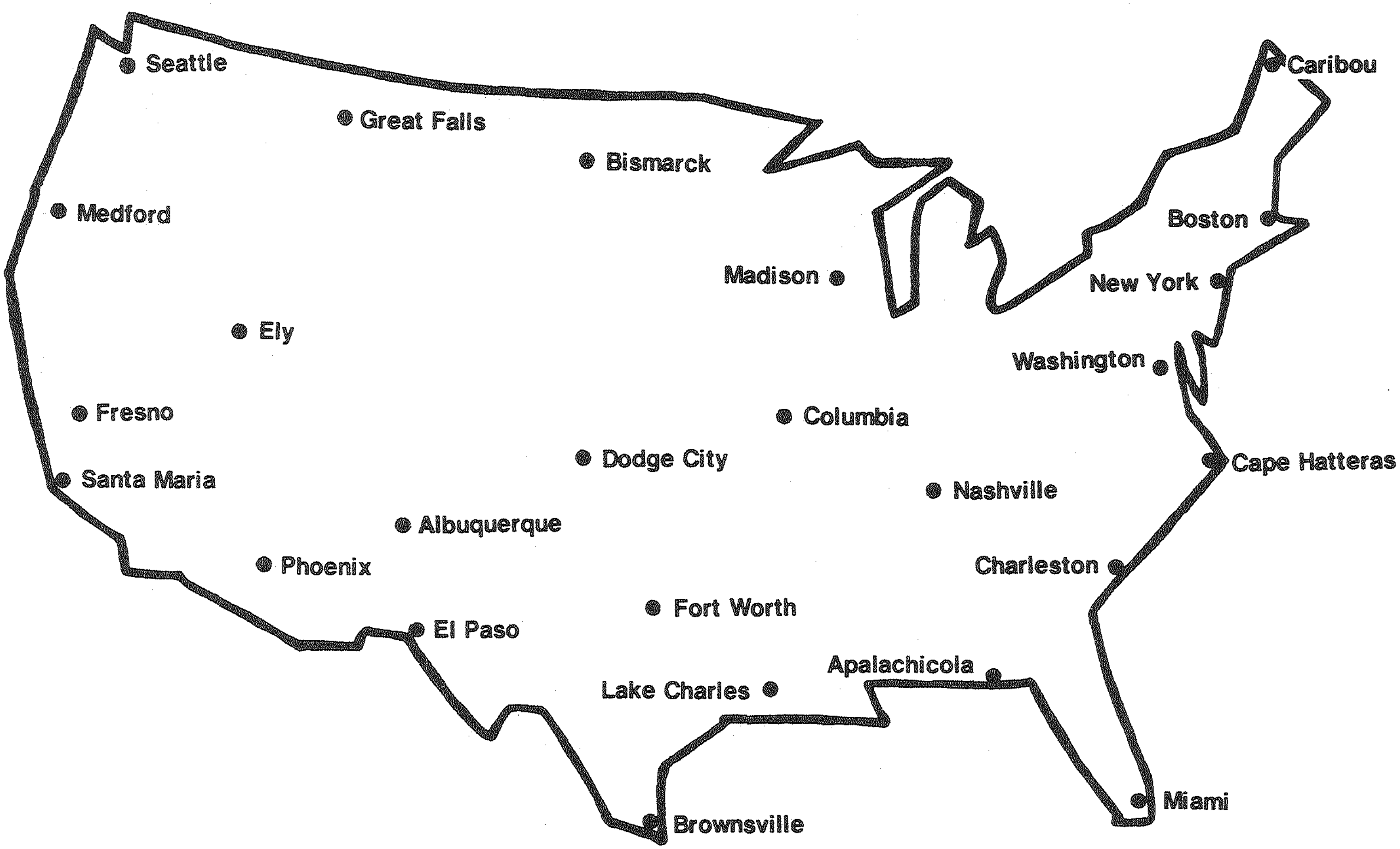

Fig. 1a

balanced view of the effects of orientation on all thermal conditioning needs of the building.

Tables Ia-Ic show results of these comparisons. The cities are arranged in order of percentage of total load which results from heating requirements for a south orientation; these tables provide a good display of orientation effects as they vary with climate. The total load for the same orientation is also given to provide a gauge of the harshness of the climate and the response of the prototype building to it. The next three columns indicate changes in heating, cooling, and total loads (in MBtu) resulting from change in orientation. The final column is percentage change in total load resulting from change in orientation. Since loads for east and west orientations were typically very similar*, their average was used to represent both orientations.

The last column of each table has been mapped (Figs. 2-4) to give a better indication of regional effects of orientation. The regions marked on each map are for purposes of discussion only, and are not precisely defined.

3.1. East/West Vs. South Orientation

Differences between east/west orientation and south orientation are largely the result of two solar effects: (1) solar gain through east or west windows is lower than through south windows during winter, resulting in higher heating loads for east and west glazing, and (2) solar gain through east or west glazing is higher than through south windows during summer, resulting in higher cooling loads for east and west glazing. The latter effect is particularly pronounced for windows with overhangs, because overhangs are most effective in shading south windows from direct sun.

Region I of Fig. 2 is an area of long heating seasons in which virtually no cooling loads occur. The solar gain through south windows is effective at offsetting heating loads while excess summer gain through east and west windows has little effect on the small cooling loads. The difference of 12-20% in loads in this region shows a clear advantage for south orientation, although south windows alone will obviously not solve the whole heating problem.

Region II of Fig. 2 is an area of mixed loads, where both heating and cooling are important to provide adequate comfort levels. In this region, the winter advantage of south glazing is similar to that of

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* Loads due to east windows will occur at different times from those due to west windows. With our assumption of full-time occupancy and moderate thermal mass levels to spread solar effects across several hours, this difference in timing caused very little difference in integrated loads. However, if thermal mass were minimal and/or temperature were allowed to float during daytime periods, the sensitivity of building loads to east vs. west glazing would probably be more pronounced.

Heating and Cooling LOADS
Average of EAST and WEST Orientation:
% Greater than SOUTH Orientation

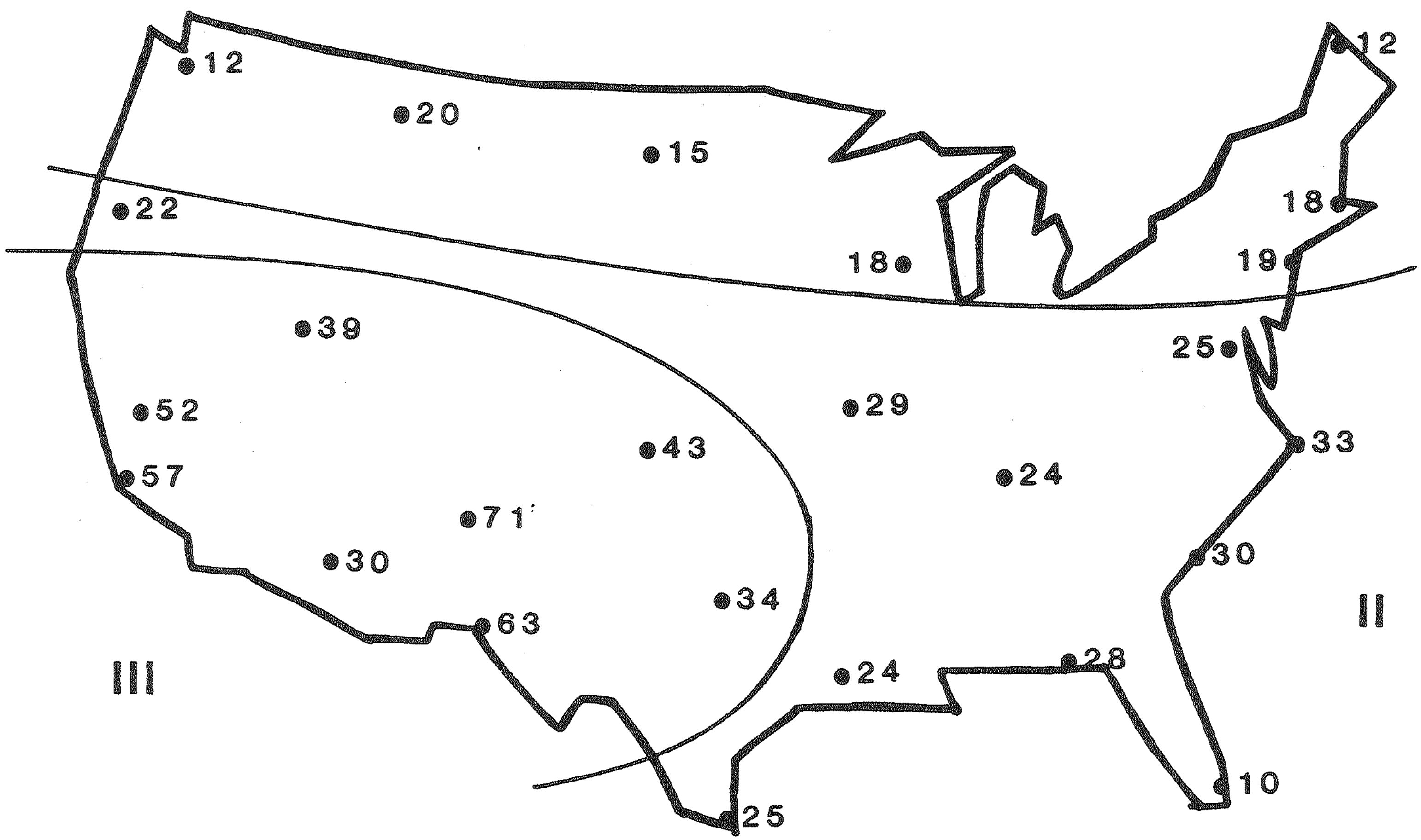

Fig.2

TABLE Ia: LOADS		South Orientation		East-West Orient.+: Increase over South Orient.			
City	State	Heating, % of Total	Total (MBtu)	Heating (MBtu)	Cooling (MBtu)	Total (MBtu)	Total (%)
Caribou	ME	99	43.7	4.9	.4	5.3	12
Seattle	WA	97	19.1	2.0	.3	2.3	12
Ely	NV	94	18.8	5.7	1.7	7.4	39 *
Bismarck	ND	93	43.1	6.0	.9	6.9	15
Great Falls	MT	93	30.2	5.2	.7	5.9	20
Madison	WI	92	33.3	4.8	1.3	6.1	18
Boston	MA	92	27.4	3.9	1.0	4.9	18
New York	NY	87	23.5	3.7	0.8	4.5	19
Medford	OR	78	16.6	2.4	1.2	3.6	22
Columbia	MO	74	26.3	4.2	3.5	7.7	29
Dodge City	KS	71	23.5	5.7	4.3	10.0	43 *
Washington	DC	69	23.2	3.6	2.2	5.8	25
Santa Maria	CA	65	2.7	1.6	.1-	1.5	57 **
Albuquerque	NM	61	11.6	4.3	3.8	8.1	71 *
Nashville	TN	53	22.0	2.7	2.9	5.6	24
Cape Hatteras	NC	37	18.8	2.9	3.4	6.3	13
Fresno	CA	34	14.9	2.3	5.4	7.7	52 *
Fort Worth	TX	27	22.7	2.5	5.2	7.7	34
Charleston	SC	23	18.3	2.4	3.2	5.6	30
El Paso	TX	20	14.5	2.0	7.1	9.1	63 *
Lake Charles	LA	15	21.7	1.1	4.1	5.2	24
Apalachicola	FL	8	21.3	1.1	4.9	6.0	28
Brownsville	TX	4	26.7	.3	6.3	6.6	25
Phoenix	AZ	3	27.7	1.0	7.3	8.3	30
Miami	FL	0	27.7	.0	2.7	2.7	10

* Figures for the desert climate are often much higher than comparable areas because the cold nights and hot, sunny days are ideal for reduction of both heating and cooling loads by proper orientation and appropriate levels of thermal mass.

** The percentage increase for Santa Maria is unexpectedly high only because of the extremely low baseline loads in the mild California coastal climate. These are treated as anomalous points throughout the discussion.

\+ Average of East and West Orientations.

regions farther north. Added to this is the advantage of less excess solar gain through south glazing during summer, resulting in lower cooling loads. The sites in this region near the Gulf of Mexico show a similar advantage in south orientation, although this is predominantly due to lower cooling loads. Most locations in this region show an increase in total load of 22 to 33% in changing from south orientation to east or west orientation.

Region III of Fig. 2 is an area of varied climates, from nearly all heating (Ely, NV) to nearly all cooling (Phoenix, AZ). However, all these locations have dry, sunny climates. Because of the dominant influence of solar gain on the incremental loads being investigated, both heating and cooling season advantages of south glazing over east or west are accentuated, resulting in the largest differences of the three regions, 30-71%.

3.2. East/West Vs. North Orientation

The solar effects on north windows are minimal. They receive no beam sunlight in winter, and only a small amount in summer. During the heating season, east and west orientations will provide some solar gain, although this is limited, especially in higher latitudes. In the cooling season, however, east and west windows will result in overheating from solar gain, as seen in the previous section, while solar gain through a north window will not add appreciably to the cooling load.

Region I of Fig. 3 is an area of high heating loads and low cooling loads. Beneficial solar gain through east and west windows adds up over the long heating season, and tend to balance overheating from the same source which occurs during the short cooling season. Since both effects are relatively small, it is not surprising to find total loads for east and west orientations differing by less than 3% from north orientation.

Region II of Fig. 3 contains climates where annual heating and cooling loads are both significant. Here, excess solar gain through east and west orientations occurs over a longer period, and the effect on cooling loads is more pronounced. In this region the total load for east and west orientations ranges between 8 and 19% higher than for north orientation.

Region III of Fig. 3 is a region where cooling loads dominate. The very long cooling season provides ample opportunity for solar gain from east or west to produce overheating. The detrimental effect of this solar gain produces the highest percentage increases over north orientation, 22-44%. As expected, the highest percentage increases correspond to the sunniest climates.

The results of this comparison, combined with those of the previous section, demonstrate disadvantages of east or west orientation. The energy situation is almost always better for either north or south orientations. A street system with long east-west streets encourages both north and south orientations and has the possibility of facing all houses toward the street (half toward north, half toward south), or choosing to face all of them in one direction. The choice will depend

Heating and Cooling LOADS
Average of EAST and WEST Orientation:
% Greater than NORTH Orientation

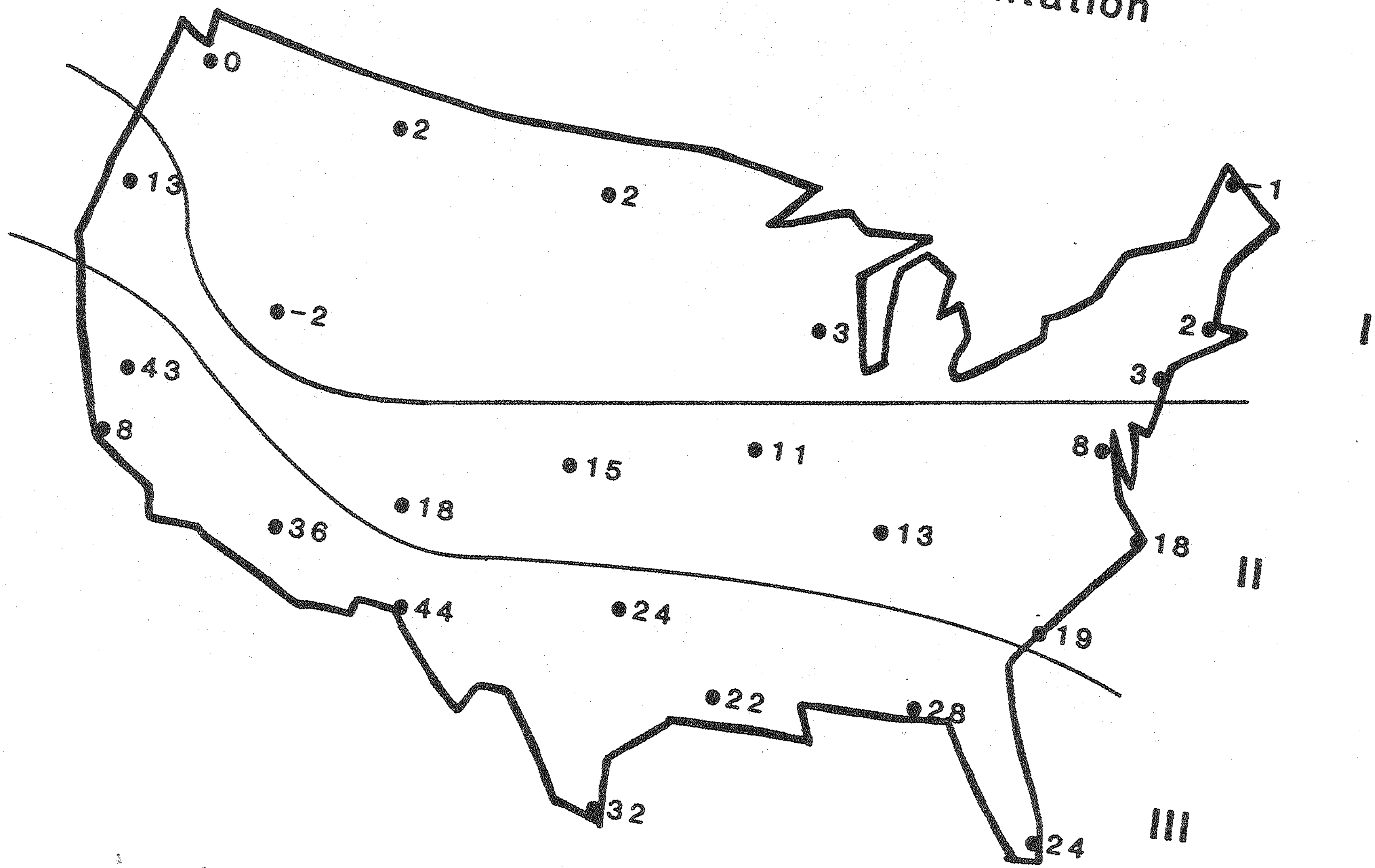

Fig.3

TABLE Ib: LOADS		South Orientation		East-West Orient.+: Increase over North Orient.			
City	State	Heating, % of Total	Total (MBtu)	Heating (MBtu)	Cooling (MBtu)	Total (MBtu)	Total (%)
Caribou	ME	99	43.7	1.0-	.6	.4-	1-
Seattle	WA	97	19.1	.4-	.5	.1	0
Ely	NV	94	18.8	2.5-	1.9	.6-	2-
Bismarck	ND	93	43.1	.8-	1.8	1.0	2
Great Falls	MT	93	30.2	.8-	1.6	.8	2
Madison	WI	92	33.3	.6-	1.7	1.1	3
Boston	MA	92	27.4	.6-	1.3	.7	2
New York	NY	87	23.5	.4-	1.1	.7	3
Medford	OR	78	16.6	.3-	2.6	2.3	13
Columbia	MO	74	26.3	.4-	3.8	3.4	11
Dodge City	KS	71	23.5	.9-	5.1	4.2	15
Washington	DC	69	23.2	.6-	2.8	2.2	8
Santa Maria	CA	65	2.7	.3-	.6	.3	8
Albuquerque	NM	61	11.6	1.4-	4.4	3.0	18
Nashville	TN	53	22.0	.4-	3.5	3.1	13
Cape Hatteras	NC	37	18.8	.4-	4.1	3.7	18
Fresno	CA	34	14.9	.1-	6.9	6.8	43 *
Fort Worth	TX	27	22.7	.3-	6.2	5.9	24
Charleston	SC	23	18.3	.1-	4.0	3.9	19
El Paso	TX	20	14.5	.6-	7.9	7.3	44 *
Lake Charles	LA	15	21.7	.2-	5.1	4.9	22
Apalachicola	FL	8	21.3	.2-	6.1	5.9	28
Brownsville	TX	4	26.7	.1-	8.2	8.1	32
Phoenix	AZ	3	27.7	.1-	9.7	9.6	36 *
Miami	FL	0	27.7	.0	5.9	5.9	24

* Figures for hot, dry climates are often much higher than comparable areas because the hot, sunny days are ideal for reduction of cooling loads by proper orientation and appropriate levels of thermal mass.

\+ Average of East and West Orientations.

on both planning (providing an incentive for facing a building toward the center of a block) and design of individual houses. In order to investigate the importance of encouraging a single orientation for all residences, rather than a pair of opposite orientations, loads were compared for north and south orientations.

3.3. North vs. South Orientation

Again, major differences in loads between north and south orientations result from differences in solar gain during the heating and cooling seasons. In winter, substantial solar radiation can be accepted through south windows, while no direct beam radiation at all is available to north windows. In summer, some direct beam radiation will be transmitted through south windows, although it is reduced by high angles of incidence and the limited time that the sun appears in the south sky. Even less solar radiation is transmitted through north windows during the same period. In all U.S. climates there is a distinct advantage to south windows during the heating season, and in most climates a much smaller advantage to north windows during the cooling season.

In Region I of Fig. 4, heating loads account for 20-99% of total loads of the building. Throughout this area, advantages of south orientation in the heating season outweigh small disadvantages during the cooling season. This region covers the great majority of the country. North orientation proves to have total loads 6-17% higher than south orientation. The more dominant the heating load, the greater the difference.

Region II of Fig. 4 is an atypical area where heating loads dominate and where there is a very large solar potential (it might be characterized as "high desert"). With this combination, solar gain through south windows during the heating season is able to reduce loads to a very large degree. The result is a much larger advantage of south glazing over north; total load for north orientation is 25-45% higher than for south.

Region III of Fig. 4 is a region in which heating loads play only a minor role (15% or less of total load). In this area, winter solar gain is of little help, and may even cause overheating if the cooling season extends over the entire year. In contrast, summer overheating from south windows can accumulate over the long cooling season, causing severe increases in cooling loads. The result is a region in which the two effects may balance (a 1% advantage for south orientation) or overheating may even dominate (a 5-12% advantage for north orientation)!

The implications are quite clear. Over the majority of the country, south orientation gives a modest advantage and is preferred. In the high desert region, south orientation is substantially better, and should be strongly encouraged. In the warmest areas along the southern edge of the country, the choice is not so important, although in the very warmest climates, a north orientation is preferred.

The reader should be cautioned again that these results do not consider any special window controls or even common window management such

Heating and Cooling LOADS

NORTH Orientation:

% Greater than SOUTH Orientation

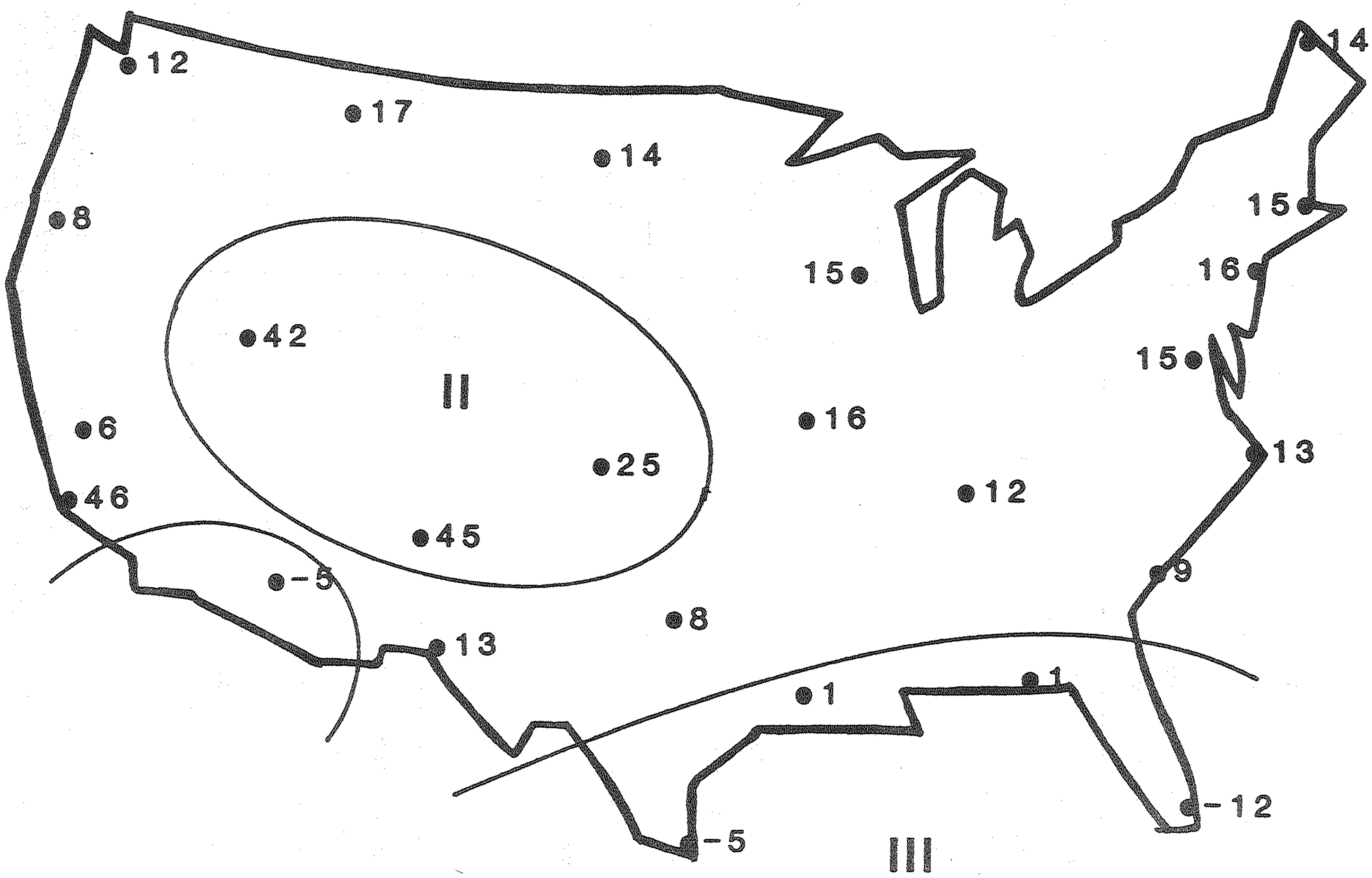

Fig.4

TABLE Ic: LOADS		South Orientation		North Orientation: Increase over South Orient.			
		Heating,	Total	Heating	Cooling	Total	
City	State	% of Total	(MBtu)	(MBtu)	(MBtu)	(MBtu)	(%)
Caribou	ME	99	43.7	5.9	.2-	5.7	14
Seattle	WA	97	19.1	2.4	.2-	2.2	12
Ely	NV	94	18.8	8.2	.3-	7.9	42 *
Bismarck	ND	93	43.1	6.7	.9-	5.8	14
Great Falls	MT	93	30.2	6.0	.9-	5.1	17
Madison	WI	92	33.3	5.4	.4-	5.0	15
Boston	MA	92	27.4	4.5	.2-	4.3	15
New York	NY	87	23.5	4.1	.4-	3.7	16
Medford	OR	78	16.6	2.8	1.4-	1.4	8
Columbia	MO	74	26.3	4.6	.4-	4.2	16
Dodge City	KS	71	23.5	6.6	.8-	5.8	25 *
Washington	DC	69	23.2	4.2	.6-	3.6	15
Santa Maria	CA	65	2.7	1.9	.7-	1.2	46 **
Albuquerque	NM	61	11.6	5.7	.5-	5.2	45 *
Nashville	TN	53	22.0	3.1	.6-	2.5	12
Cape Hatteras	NC	37	18.8	3.3	.8-	2.5	13
Fresno	CA	34	14.9	2.4	1.5-	.9	6
Fort Worth	TX	27	22.7	2.7	1.0-	1.7	8
Charleston	SC	23	18.3	2.5	.8-	1.7	9
El Paso	TX	20	14.5	2.6	.8-	1.8	13
Lake Charles	LA	15	21.7	1.3	1.0-	.3	1
Apalachicola	FL	8	21.3	1.3	1.2-	.1	1
Brownsville	TX	4	26.7	.4	1.9-	1.5-	5-
Phoenix	AZ	3	27.7	1.1	2.5-	1.4-	5-
Miami	FL	0	27.7	.1	3.2-	3.1-	12-

* Figures for cool, high, dry climates are often much higher than comparable areas because the cold nights and hot, sunny days are ideal for reduction of both heating and cooling loads by proper orientation and appropriate levels of thermal mass.

** The percentage increase for Santa Maria is unexpectedly high only because of the extremely low baseline loads in the mild California coastal climate. These are treated as anomalous points throughout the discussion.

as drawing blinds (although the ventilation simulation can be said to approximate the effect of opening windows at appropriate times). Thus, where overheating effects play a major role in the results, it should be kept in mind that these effects might be reduced by providing a larger degree of solar control.

3.4. Effect of Orientation on Peak Loads

One concern about large window areas placed in position to accept large solar gain, is that they will increase peak loads, even though they may reduce annual loads on the building. Tables II and III show the effect of orientation on predicted peak heating and cooling loads in the 25 climates for which these simulations were performed. Again, the cities are listed in order according to dominance of heating load. The first column of peak load data is the peak when the building is oriented toward south. The last three columns are increases in peaks when the building is turned away from a south orientation. The data in these tables are in units of KBtu, not MBtu and percentages as used earlier.

Heating peaks, listed in Table II, showed little sensitivity to orientation. This is not surprising, since the peak load normally occurs in the early morning on a winter day when the furnace is trying to pull the building temperature up at the end of the setback period; Because this occurs so early in the day, solar gain has little effect on this peak, and orientation is unimportant. Nevertheless, south orientation consistently gives the lowest peak heating load, usually between 100 and 3000 Btu/hour lower than other orientations. Larger differences resulting from orientation occur in the southern part of the U.S., possibly because longer winter days and milder winter climate allow some thermal storage to carry over until morning.

Cooling peaks, listed in Table III, show some significant variation between different orientations. These results are harder to analyze than total loads because they are less consistent. They are much more dependent on specific weather and building conditions at the particular hour when the peak occurs. Thus, there will be exceptions to almost any generalization one might make about the effect of orientation on peak loads, and it is important that the causes responsible for specific changes be identified.

When compared to south, peak cooling loads for east orientations are consistently higher, generally 1000-6000 Btu/hour. This is true over a range of climates, and can be explained by high solar loads on east windows during summer days, when peak cooling is likely to occur. There are five examples of lower cooling loads with east orientation, however. Presumably these are peaks which occur on days which start out cloudy, minimizing east window solar gain, then clear to allow maximum solar gain from south windows.

West orientation has the highest peak cooling load of all four orientations in all 25 climates. This is not surprising, since solar gain through west windows during summer is very high. The gain comes at the worst time of day from a cooling standpoint, early to late afternoon, and in most climates that part of the day is most likely to be

TABLE II			PEAK HEATING LOADS (KBtu/hour)			
		Heating, % of Total		Increase over South Orientation		
City	State	South	South	East	West	North
Caribou	ME	99	43.8	.1	.3	.2
Seattle	WA	97	24.6	.1	.0	.1
Ely	NV	94	33.6	.9	1.5	1.6
Bismarck	ND	93	51.5	.3	.4	.3
Great Falls	MT	93	40.1	.1	.1	.1
Madison	WI	92	39.2	.7	.7	.7
Boston	MA	92	32.5	.1-	.1	.1
New York	NY	87	30.0	.1	.4	1.3
Medford	OR	78	18.1	1.8	1.7	1.5
Columbia	MO	74	33.9	.6-	.5	.8
Dodge City	KS	71	33.4	.3	.3	.3
Washington	DC	69	29.0	.5-	.1	.6
Santa Maria	CA	65	10.3	5.1	4.8	4.5
Albuquerque	NM	61	22.5	1.3	1.6	1.5
Nashville	TN	53	25.3	.8	1.7	1.5
Cape Hatteras	NC	37	22.8	1.4	1.1	1.2
Fresno	CA	34	16.5	.6	.5	.4
Fort Worth	TX	27	22.9	2.7	2.7	2.6
Charleston	SC	23	17.4	2.5	3.6	3.8
El Paso	TX	20	17.4	2.7	3.0	2.5
Lake Charles	LA	15	18.9	2.3	1.9	2.5
Apalachicola	FL	8	15.6	1.7	2.0	1.8
Brownsville	TX	4	12.4	.9	1.2	1.4
Phoenix	AZ	3	13.9	1.3	1.3	1.2
Miami	FL	0	5.2	.9	1.1	2.4

TABLE III			PEAK COOLING LOADS (KBtu/hour)			
		Heating, % of Total		Increase over South Orientation		
City	State	South	South	East	West	North
Caribou	ME	99	11.2	.0	7.3	4.0-
Seattle	WA	97	8.1	2.4	7.8	2.4-
Ely	NV	94	9.0	3.0	10.9	2.3-
Bismarck	ND	93	15.0	4.7	5.5	2.4-
Great Falls	MT	93	15.9	3.1-	3.3	8.2-
Madison	WI	92	11.5	3.4	7.6	.0
Boston	MA	92	10.2	3.6	12.1	.0
New York	NY	87	12.4	.2-	5.5	1.6-
Medford	OR	78	15.9	2.2-	4.4	5.9-
Columbia	MO	74	13.4	4.0	9.6	.1
Dodge City	KS	71	18.5	.2-	7.1	4.4-
Washington	DC	69	13.6	1.8	5.8	1.7-
Santa Maria	CA	65	14.1	2.2-	4.1	7.7-
Albuquerque	NM	61	13.9	5.6	11.4	.9-
Nashville	TN	53	14.4	.7	6.5	2.0-
Cape Hatteras	NC	37	14.1	1.7	5.5	2.9-
Fresno	CA	34	17.1	1.7	8.5	3.6-
Fort Worth	TX	27	15.6	3.0	9.7	.2
Charleston	SC	23	13.6	2.6	6.3	1.7-
El Paso	TX	20	13.2	7.9	8.8	.2
Lake Charles	LA	15	13.5	4.7	8.4	.4-
Apalachicola	FL	8	15.1	5.0	2.9	2.0-
Brownsville	TX	4	16.9	2.6	3.0	3.7-
Phoenix	AZ	3	18.2	3.9	8.6	.0
Miami	FL	0	16.7	.7	1.6	3.6-

clear and sunny. The combination of these effects produces a consistent and obvious pattern. In most climates, west orientation has a cooling peak 3,000-12,000 Btu/hour higher than the same building in a south orientation. This is true even in those areas with rather small cooling loads. In those cases, the difference in peak load may determine whether mechanical cooling is even a worthwhile investment.

Percentage effects are large: the increase in peak cooling load in shifting from south to west ranges from 10% to 121% with an average increase of 53% for the twenty-five locations. To meet these loads, cost increases for added capacity of air-conditioning at the house and electric generation at the utility could be severe.*

North orientation has the lowest cooling peaks of all four orientations, except in a few cases where it is virtually equivalent to the peak associated with south orientation. This is not surprising, as it is the only orientation with virtually no direct solar gain through most of its windows. Of particular interest is the comparison between peaks in buildings with north and west orientations. The north orientation has peaks 7,000-13,000 Btu lower than west orientation. Again, there are locations where this may affect the decision about whether or not to install a mechanical cooling system. When one combines this peak load information with annual consumption results (shown in Fig. 3 and Table Ib), a much stronger case is made for the advantages of north orientation over west, even in the northern tier where differences in total load are minimal.

Residential utility bills typically do not account for the size and time of the peak load, so to the consumer the primary advantage of reduced peak is smaller equipment. To the utility, however, both size and timing of the peak load are important. This is especially true for summer peaking utilities, where the maximum electric demand typically occurs during a mid-to-late summer afternoon.

The times of occurrence of cooling peaks vary substantially with orientation. As Table IV shows, when the building is oriented toward the west, 20 of the 25 sites have a peak cooling load during June, July, or August at hour 17 (4-5 PM), about the time a utility peak would occur. Nearly as many sites show cooling peaks during the same period with north orientation, although the magnitude is always much less. East orientation tends to produce summer peaks, but nearly half the

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* There are other deleterious effects of west glazing which are not apparent from the results. For these simulations thermal control was based strictly on air temperature, which is only a partial indicator of comfort. Large solar gain through west windows occurs during the afternoon of summer days, causing an immediate increase in mean radiant temperature during late afternoon. By heating the structure, it causes a higher mean radiant temperature during the evening and into the night as well. As a result, west facing windows seriously degrade comfort conditions during periods of high residential occupancy.

TABLE IV			TIME OF PEAK COOLING LOADS (month/hour)							
		Heating, % of Total	South		East		West		North	
City	State	South	mon	hr	mon	hr	mon	hr	mon	hr
Caribou	ME	99	Aug	13	Jun	17	Jun	17	Jun	18
Seattle	WA	97	Sep	14	Jul	17	Jul	17	Jul	17
Ely	NV	94	Sep	14	Jul	17	Jul	17	Jul	18
Bismarck	ND	93	Aug	14	Aug	10	Aug	17	Aug	17
Great Falls	MT	93	Oct	14	Jul	9	Jul	17	Jul	16
Madison	WI	92	Jun	17	Jun	17	Jun	17	Jun	17
Boston	MA	92	Jul	17	Jul	17	Jul	17	Jul	17
New York	NY	87	Aug	12	Jul	17	Jul	17	Aug	12
Medford	OR	78	Oct	14	Jun	17	Jun	17	Aug	17
Columbia	MO	74	Jul	17	Jul	17	Aug	17	Jul	17
Dodge City	KS	71	Oct	14	Aug	17	Aug	17	Aug	17
Washington	DC	69	Oct	14	Aug	9	Aug	17	Aug	17
Santa Maria	CA	65	Oct	13	May	17	May	17	Jul	17
Albuquerque	NM	61	Oct	15	Jul	17	Jul	17	Jul	17
Nashville	TN	53	Sep	14	Jul	17	Sep	17	Aug	17
Cape Hatteras	NC	37	Oct	14	Jun	9	Sep	17	Jul	17
Fresno	CA	34	Oct	14	Jun	17	Jul	17	Jul	17
Fort Worth	TX	27	Aug	14	Aug	17	Aug	17	Aug	13
Charleston	SC	23	Oct	14	Jul	9	Jul	17	Jul	17
El Paso	TX	20	Jun	17	Jul	10	Jun	18	Jun	17
Lake Charles	LA	15	Oct	14	Aug	9	Jun	17	Aug	13
Apalachicola	FL	8	Oct	12	Sep	10	Jun	17	Aug	13
Brownsville	TX	4	Oct	13	Aug	9	Aug	17	Jun	12
Phoenix	AZ	3	Sep	14	Aug	17	Jul	17	Aug	17
Miami	FL	0	Jan	13	Aug	10	May	17	Jul	13

sites peak in the morning, during hours 9 and 10 (8-10 AM). This is true of 70% of the sites with higher cooling loads than heating loads, where summer peaking is most likely. With south orientation, peaks tend to occur later in the year, (in October for 12 of the sites) and early in the afternoon (before 2 PM for 20 of the sites). Of the 15 sites with greatest cooling loads, only one peaks after 2 PM during the summer months. Lower cooling peaks for south and east orientations, compared to west (Table III), are enhanced by advantageous timing.

Because heating peaks occur in early morning hours with little sun, altered orientation rarely changes the peak by as much as an hour.

3.5. Orientation Effects: Representative Cases

Eight climates were investigated in more detail, of which four are discussed here. The four were chosen because they illustrate effects postulated in the previous discussion in more detail.

The graphs in Figs. 5-11 use a common format. They show predicted heating, cooling, and total loads based on simulations of eight orientations (the four cardinal and four intermediate directions). The X-axis represents different orientations, from north on the left, through west, south, and east, and back to north on the right (north is included on both edges for visual symmetry). The vertical axis is the difference in load (heating, cooling, or total, in MBtu) between the orientation in question and south. Thus, south will always show 0 for each load. Total load is drawn with a solid line, heating with a dashed line, and cooling with a dotted line. Note that the shape of the curve between points is not known precisely; lines are included to provide visual organization to the data points.

3.5.1. A Cold Climate: Madison (Fig. 5).

In Madison, Wisconsin heating requirements dominate. For south orientation, heating load is 92% of the total load. Both heating and cooling curves are essentially symmetrical about the south orientation, although both curves show a slight bias toward lower loads in the eastern than the western sector, suggesting that minimum total load may occur somewhere slightly east of south.

Cooling load is greatest when orientation is due east or west, and declines when orientation is changed toward either north or south. North is very slightly better than south, due to lower solar gain. West induces higher cooling loads than east, most likely due to morning clouds or the more opportune timing of morning solar gain through east windows.

The most striking changes in heating load come when the building is turned away from south toward either east or west. The highest heating loads occur when orientation is toward northeast or northwest. These orientations have minimum winter solar gain. The north orientation is a little better than northeast or northwest, because windows mounted in the opposite wall (which constitute 25% of total glazing area) face directly south. By having these smaller windows face directly south

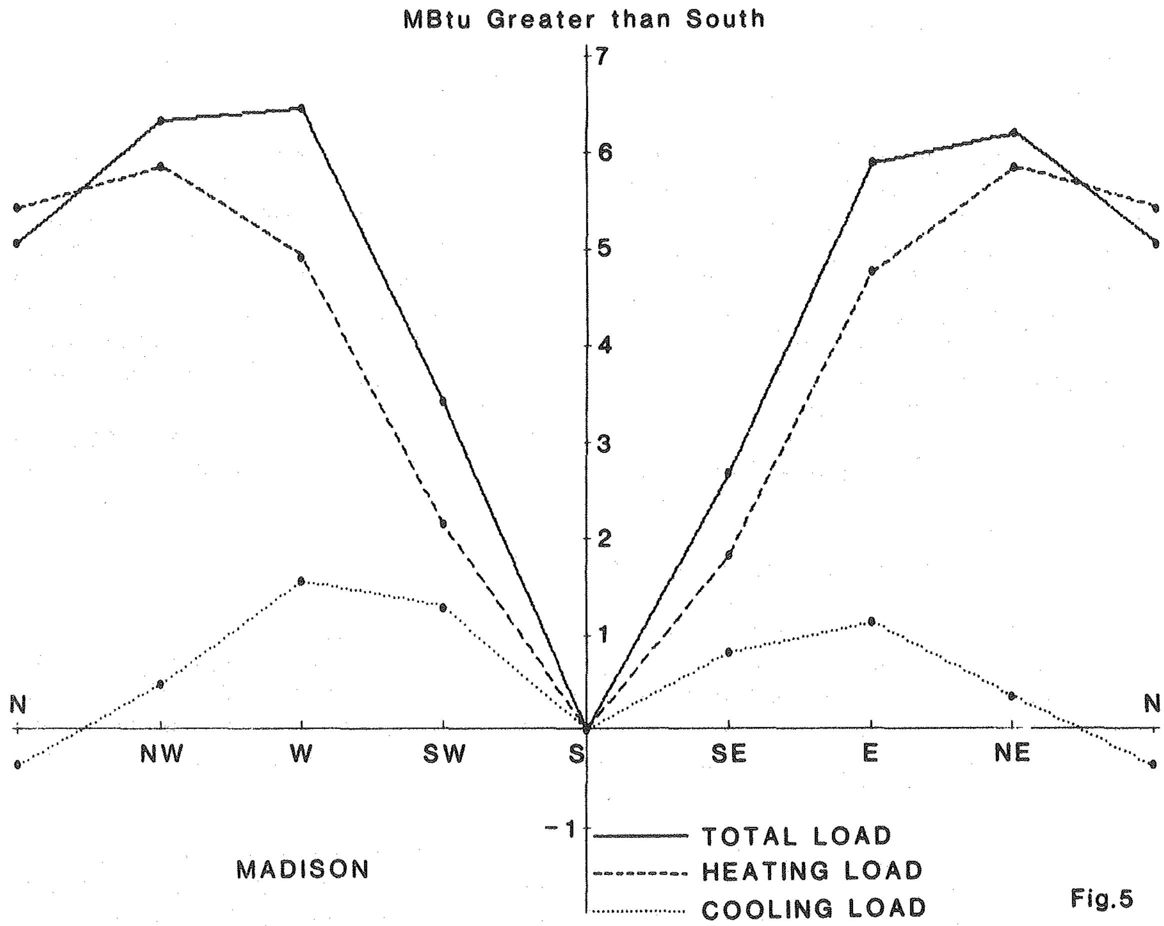

Fig.5

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rather than southeast or southwest, greater solar gain accepted through these windows more than offsets small reductions in solar gain resulting from facing the other 75% of the glazing north rather than northeast or northwest.

In this cold climate, south orientation is clearly best, southeast and southwest are not too bad, and worst loads occur at the other orientations, which are about equally bad. The dominant effect of orientation is solar gain during the heating season.

3.5.2. A Hot Climate: Miami (Fig. 6).

In Miami, Florida cooling loads dominate. For south orientation, heating accounts for less than 1% of total load in the prototype building, and shows virtually no change with orientation.

Cooling, however, shows a pronounced increase as orientation is changed away from south, and reaches its highest levels at east and west orientations. An even more pronounced decrease occurs when the building is turned to northeast, northwest, and especially north. The last orientation is much lower than any others. This is expected, as solar gain increases cooling load, and north orientation has the least solar impact. Even south windows will have substantial solar gain, because the cooling season stretches so far into winter. East orientation has a higher cooling load than west, but the reasons for this are not obvious. One possible explanation is that solar gain in the morning is stored in thermal mass long enough to become a problem in the hottest afternoon hours, whereas afternoon sun does not have an effect until cooler evening hours.

In this hot climate, north orientation is best, northeast, northwest, and south are reasonable, and the remaining four orientations have the worst influence on total loads of the prototype building. One additional point to be kept in mind is that low heating loads allow the possibility of eliminating heating equipment altogether. South and southeast orientations show the best potential for such a refinement.

3.5.3. A Mixed Climate: Nashville (Fig. 7).

In Nashville, Tennessee heating and cooling requirements are of roughly equal importance. For south orientation, heating accounts for 53% of the total load. The total load is greatest at east and west orientations. This results from the advantageous effect of south glazing on both heating and cooling loads and the advantageous effect of north glazing on cooling load.

The influence of orientation on cooling loads is quite similar to that seen in Madison, although effects are somewhat magnified due to the considerably longer cooling season in Nashville. The largest loads occur with east and west orientations, while north orientation has slightly lower cooling loads than south.

The influence of orientation on heating loads is also similar to that of Madison, except that the advantage of very high solar gain

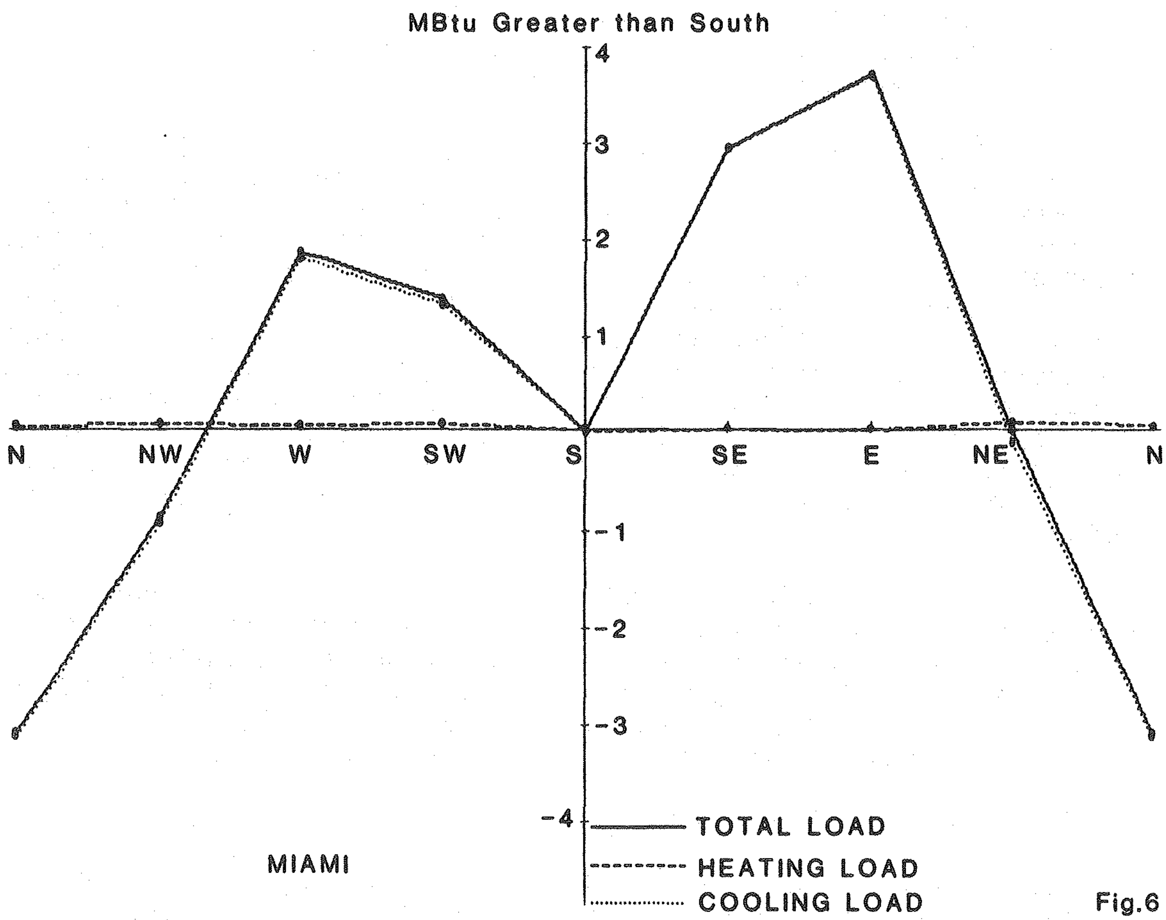

Fig.6

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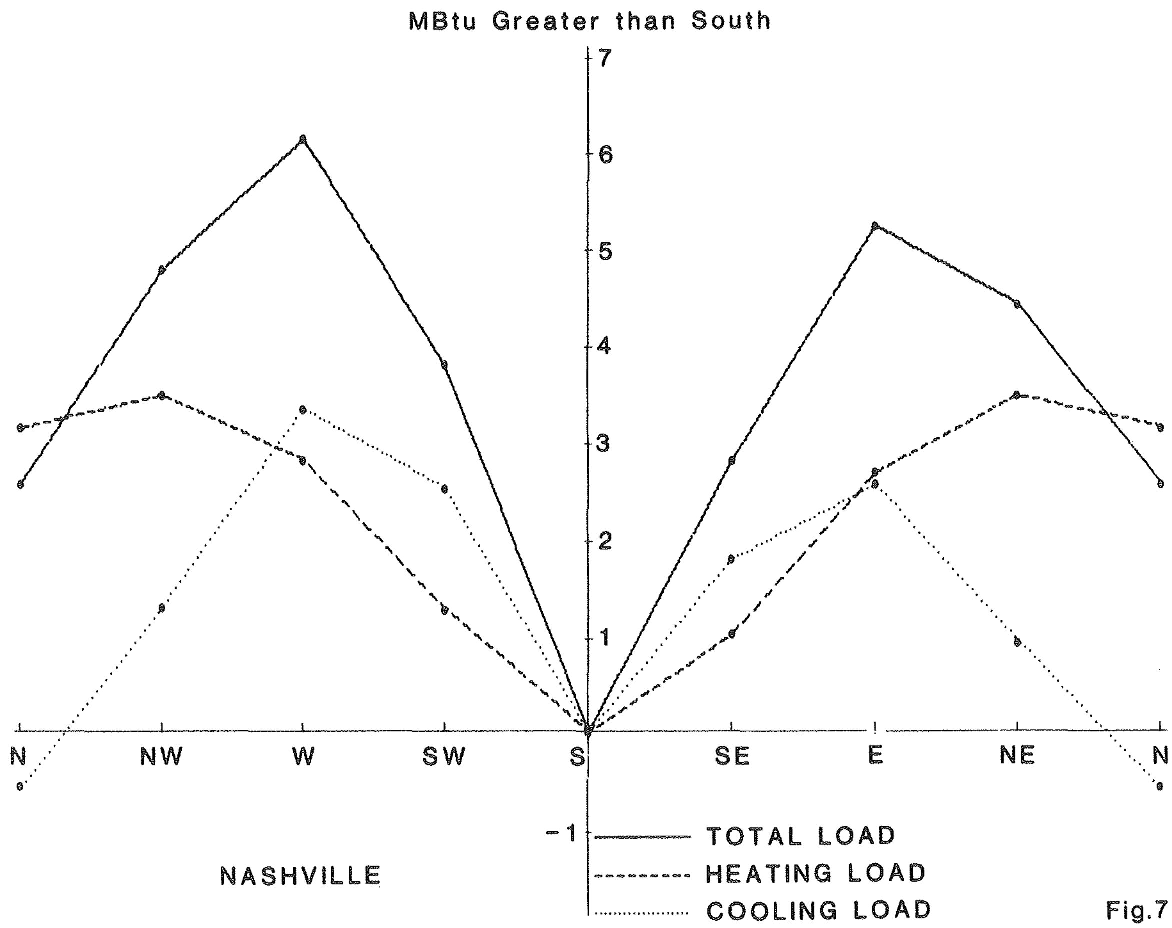

Fig.7

XBL 834-9084

through south windows, although significant, is not as pronounced in Nashville. Again, north orientation produces a lower heating load than off-north orientations, due to the benefit of having 25% of the glazing area facing directly south. West orientations have slightly higher heating loads than east, probably due to the desirable timing of morning solar gain.

Because of the equal weight of heating and cooling, total loads reflect effects of both. The lowest total load occurs for a south orientation. Southeast, southwest, and north orientations have total loads about 3 MBtu higher than for south. East and west orientations are again worst, with total loads about 6 Mbtu higher than for south.

3.5.4. A Passive Solar Climate: Albuquerque (Fig. 8).

The final example shown is Albuquerque, New Mexico. This is also a climate of mixed heating and cooling requirements, with a heating load that is 61% of the total. This particular example is shown to indicate special qualities of the southwestern high desert climate. These qualities result in an excellent match of seasonal heating and cooling loads, latitude, and a very large annual solar resource.

Cooling loads show a pattern similar to those of Madison and Nashville, and for the same general reasons, but the magnitudes of the differences between different orientations is greater. These larger differences are due largely to enhanced importance of the solar component in Albuquerque.

Heating loads show some interesting differences from patterns produced in Madison and Nashville. Southeast orientation produces loads only slightly higher than south, indicating an orientation optimal for heating somewhere between those two. As in Madison and Nashville, heating load increases rapidly as the building is turned away from south, even to northeast and northwest, but the effect is even stronger in Albuquerque than in the other two climates. Each of these effects can be attributed to the large solar resource and high percentage of clear hours.

South is the orientation with lowest total loads. Southeast orientation has total loads about 3 MBtu higher. Southwest and north orientations are almost 6 MBtu higher than south, and the other four orientations are nearly 9 MBtu higher.

In this climate, the substantial effects of simple changes of orientation, without employing any other passive solar technique, are indicative of the appropriateness (and comparative ease) of passive solar design in this climate. However, it should be emphasized that effects of orientation are substantially larger in Albuquerque than those in any other climate studied. The climate of this particular region allows relatively simple, effective passive techniques (such as simple reorientation or fixed shading) which substantially reduce energy consumption. Such techniques are generally far less effective elsewhere, and often incur greater negative effects as well. It is not justifiable to use experimental or simulation results for high desert areas

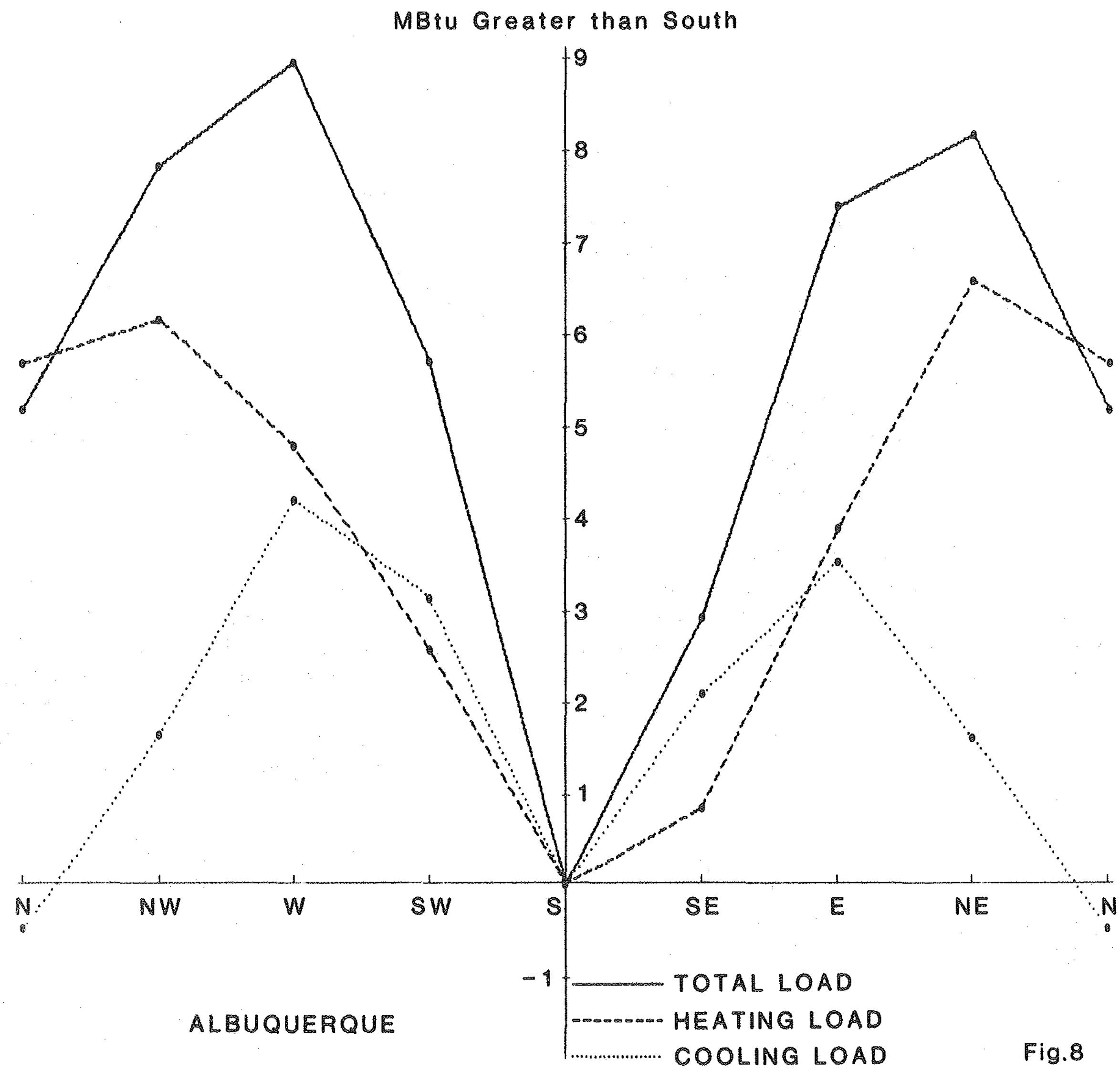

Fig.8

XBL 834-9085

to generate passive solar designs for other regions. Successful energy conserving architectural and mechanical design must be based on experiments and experience from the region in question.

3.6. Sensitivity Analysis

In order to determine the generality of results presented above, their sensitivity to some parameters which had been chosen for the prototype building were examined. Three sensitivity studies were performed on each of three representative climates: Madison, Miami, and Nashville. The figures in this section are similar to Figs. 5-8, but have three sensitivity curves added to the three baseline curves. The vertical axis shows the difference between the calculated load and the corresponding baseline load for south orientation.

3.6.1. Shading

Solar gain is obviously important to these studies, and window shading can have a significant impact on solar loads. Simulations were made with the overhang extended to 3.5 feet from the 1.5 feet used for original simulations already reported.

Not unexpectedly, shading increased heating load and decreased cooling. In Madison, the net result was a modest increase of total loads in all orientations (up to 1.1 MBtu = 3%), but not enough to alter any conclusions reached earlier. In Miami, shading reduced total load for every orientation. The maximum benefit was observed for south orientation where total load reduction was 3 MBtu (11%). Total load reductions due to added shading drops gradually toward zero as orientation is shifted from south to north. Because south and north orientations have nearly equal total loads with added shading, one can conclude that with proper overhangs south orientation can perform as well as north, even in the hottest U.S. climate. In Nashville (shown in Fig. 9), shading reduces total load in all orientations except south. However, changes in all orientations are small (less than 1 MBtu = 3%) and the conclusions of this study are not affected. Results of an orientation study with variable shading strategies for different orientations are reported in Reference [10].

3.6.2. Glass Area

To test the effect of glazing area, the major glazing area was incremented from 132 to 156 ft^2. A larger increment would have been preferable, but could not be done in the simulation -- or on the building -- without changing the windows' relationship to shading. The original 1.5 foot overhang was used. However, the small increment was enough to provide an indication of sensitivity.

In Madison (shown in Fig. 10), additional glazing increased both heating and cooling loads for every orientation but south, where a small decrease in heating load precisely balanced the increase in cooling. The maximum difference is 1.2 MBtu (3%). This would imply that for this building with unmanaged windows, south is the only orientation on which glass can be added without an energy penalty. In Miami, additional

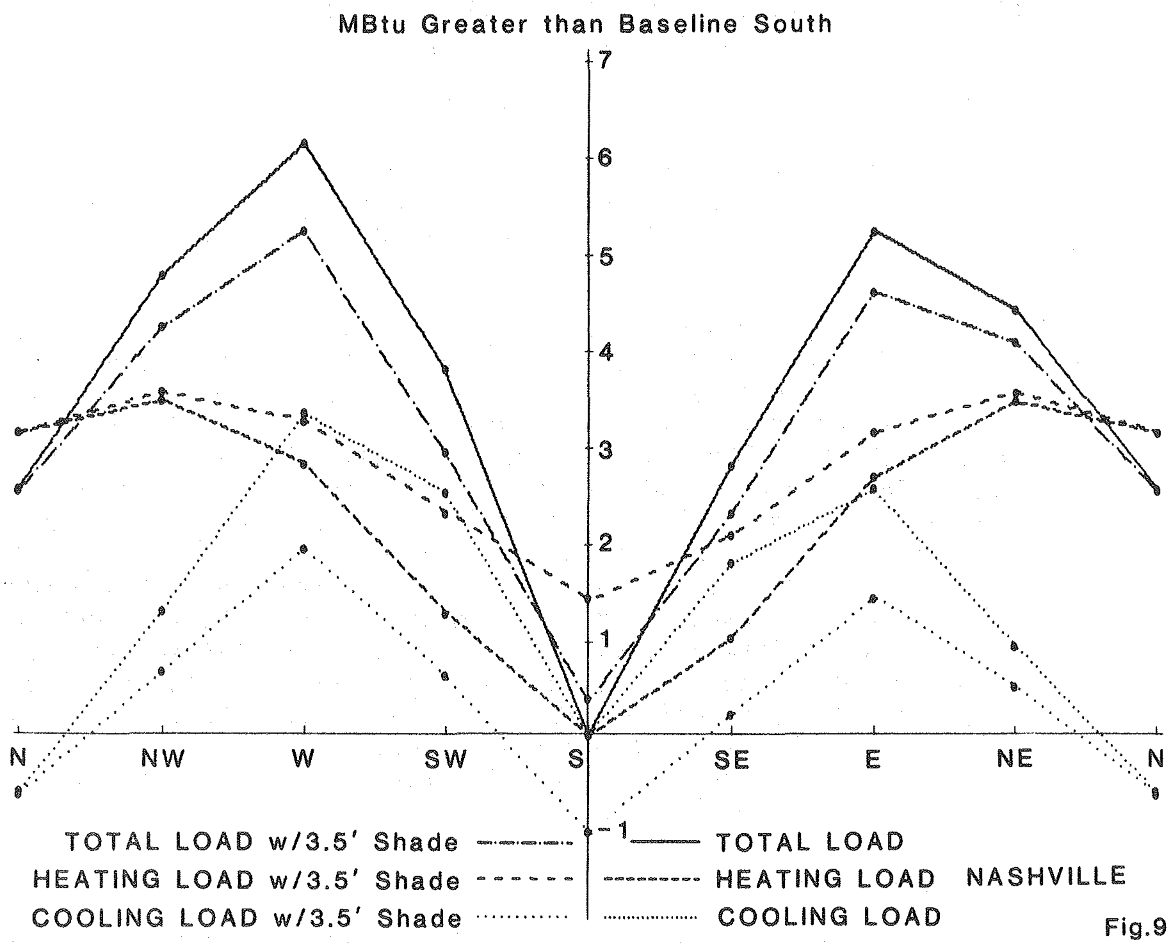

Fig.9

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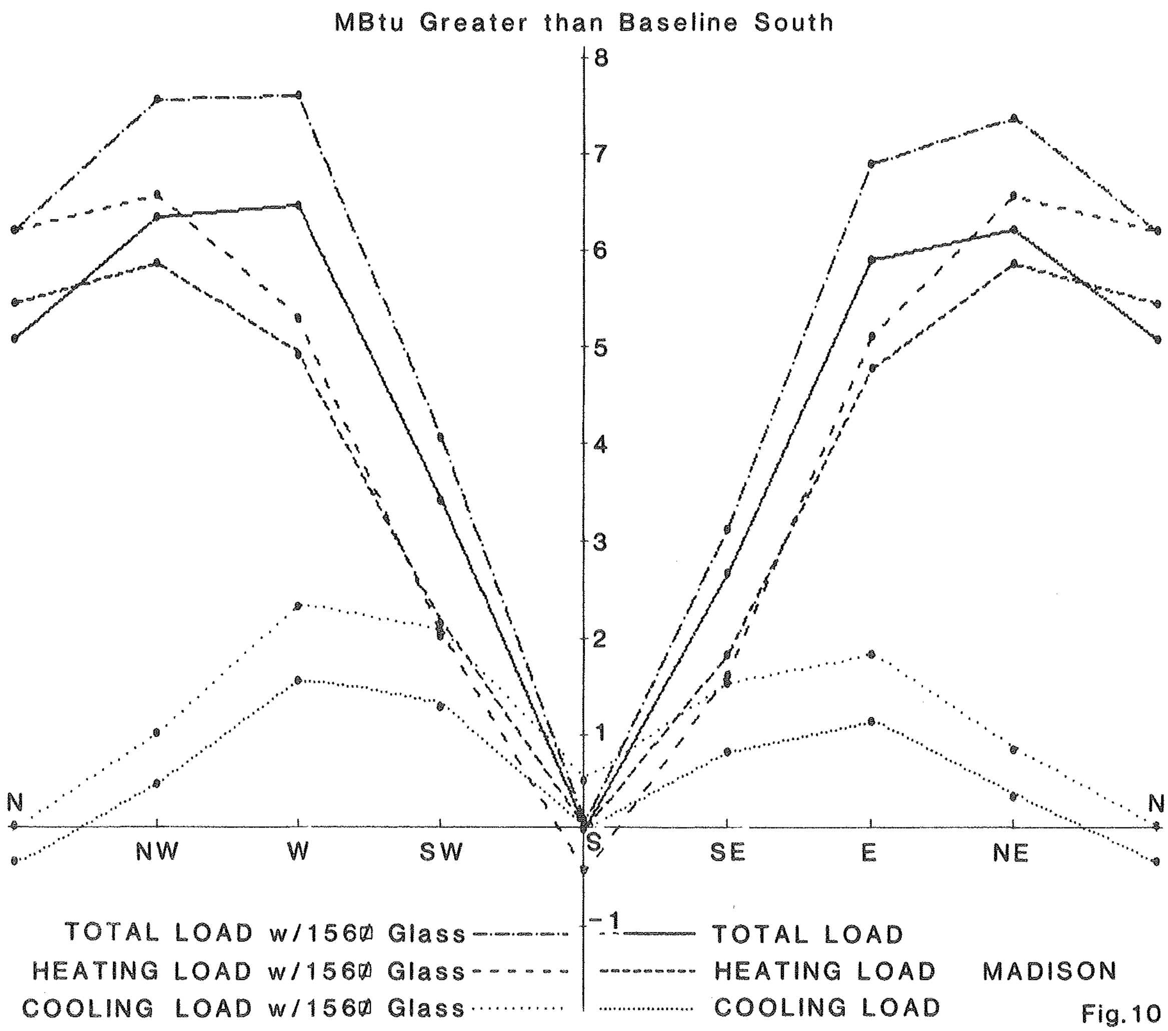

Fig.10

XBL 834-9087

glass increased total load between 2.1 MBtu (8%) for north orientation and 3.4 MBtu (12%) for east and west orientations. In Nashville, extra glass increased loads in every orientation, from 1 MBtu (4%) for north and south orientations to 1.5 MBtu (6%) for east and west. The advantage of north and south orientations over east and west was slightly enhanced by additional glazing.

3.6.3. Thermal Mass

The prototype residence has a concrete floor slab and concrete partition walls, although that portion of floor covered with carpet is quite ineffective for thermal storage. Since floor and partition construction is an important architectural and structural decision, knowledge of the sensitivity of results to lower thermal mass levels was necessary. By replacing concrete partitions with a wood and gypsum board construction, effective thermal storage was reduced considerably.

In Madison, less thermal mass produced increases in total load between 0.5 and 1.5 MBtu (1-3%), with the larger increases occurring for southern orientations. In Nashville, lower thermal mass level produced increases in total load between 1 and 2 MBtu (4-9%), with larger increases occurring for southern orientations. In neither case did reductions in structural mass alter conclusions made with the original prototype. In Miami (shown in Fig. 11), increase in total load was in the narrow range of 1.5-1.8 MBtu (5-6%) for all orientations, indicating that orientation effects are quite insensitive to change in thermal mass.

4. CONCLUSIONS

This study shows that orientation can significantly influence energy use in a moderately well insulated house, without any other passive elements or controls. This suggests that orientation is an important factor which should be considered by city planners, tract developers, and individual home builders when writing zoning and building codes, laying out subdivisions, and designing houses.

For the prototype house analyzed, the following conclusions were drawn from results of these parametric simulations:

- East and west orientations produce a higher total load (heating plus cooling) than south orientation. In shifting from south orientation to east or west orientation, total load:
  - increases 10-20% in the northern U.S.;
  - increases 20-35% in the humid southeast; and
  - increases 30-70% in the dry southwest.

- East and west orientations produce a higher total load (heating plus cooling) than north orientation. In shifting from north orientation to east or west orientation, total load:
  - changes less than 3% in the northern U.S.;
  - increases 8-20% in the middle latitudes; and

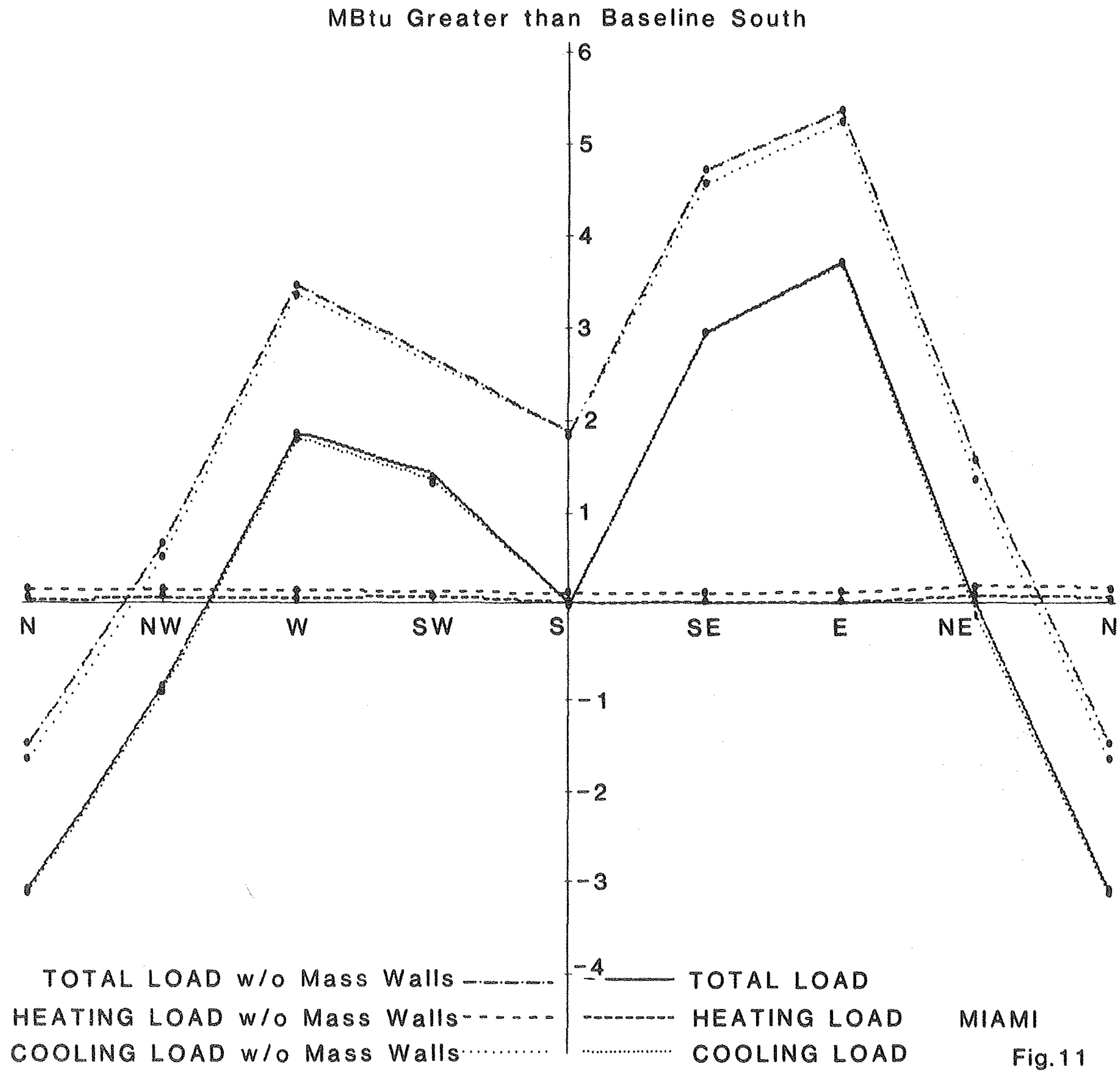

Fig.11

XBL 834-9088

- increases 20-45% in the southern U.S.

- North orientation produces a higher total load (heating plus cooling) than south orientation in all but the hottest U.S. climates. In shifting from south orientation to north orientation, total load:
  - increases by 25-45% in high desert areas where solar heating benefits of south glazing are large;
  - increases by 5-20% in most of the rest of the U.S.; and
  - decreases by as much as 12% in extreme southerly climates where cooling loads dominate.

- Cooling load peaks are generally highest for west orientation, somewhat lower for east orientation, lower still for south orientation, and lowest for north orientation. Heating peaks do not change significantly with orientation.

- Modest changes in level of thermal mass or area of the large glazing do not materially change effects of orientation described above.

- Increasing the amount of shading over windows tends to diminish the effect of orientation changes.

These findings indicate some potential benefits to be derived from a proper understanding of energy interactions between a building and its environment, particularly energy flows through glazing in the building envelope. This study has been limited to one type of glazing, two depths of overhang, two levels of structural mass, and eight orientations. Significant additional design information could be derived from parametric studies of a number of other important factors, among which are:

- variable shading around glazing;

- movable insulation;

- high R-value glazings;

- occupant comfort impacts of large glazing areas and large structural mass surfaces absorbing solar radiation;

- absorption of greater fractions of admitted sunlight directly on the most significant structural mass;

- stronger coupling of ventilation air to the most significant structural mass; and

- use of glazing for natural lighting as well as view and solar gain.

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List of Figures and Tables

Appendix 1

APPENDIX 1

PROTOTYPE PASSIVE SOLAR RESIDENTIAL BUILDING*

Introduction

In order to provide a basis for thermal analyses examining the effects of design variables on the energy consumption of residential buildings, a standardized residential prototype has been designed. The design was developed jointly by the Passive Research and Development Group at Lawrence Berkeley Laboratory and the Building Technology Branch at the Solar Energy Research Institute. Use of common baseline building parameters in thermal analyses by these and other institutions will lead to a thermal performance data base which is consistent with respect to architectural and engineering design parameters, and ensures that the research performed by the various organizations provides results which are directly comparable and internally consistent.

The purpose here is to provide an overview of the building design parameters. The prototype is described in detail in Reference [A1-1]; this reference describes the basis for the prototype's architectural and building use assumptions and describes the thermal behavior of the two major variations on the design. These variations are differentiated only with respect to assumptions regarding the thermal zoning of the structure. The baseline prototype is a three-zone structure which is intended for modeling on multizone building energy analysis computer programs such as BLAST and DOE-2. The single zone version of the prototype is appropriate for analysis with more simplified tools.

This summary of the design parameters for the three-zone version of the prototype includes overviews of (1) the architecture and its basis, (2) the thermal model, and (3) the building use parameters.

Architecture

Floor area and gross window area of the prototype are based on the design developed by S.R. Hastings of the National Bureau of Standards [A1-2]; this structure typifies much of the new residential construction and has been the basis for energy analyses for conventional buildings. In order to reflect passive design features the roofline, proportions, layout, and overhangs have been taken from residential plans developed by the Tennessee Valley Authority (TVA) for a passive solar demonstration project [A1-3]. The floor plan of the original TVA design is shown in Fig. A1-1. The thermal zones for the BLAST simulation are shown in

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* The prototype described here has served as the basis for simulations for several projects. Refer to Section 2.1 for a description of alterations which have been made for this particular study.

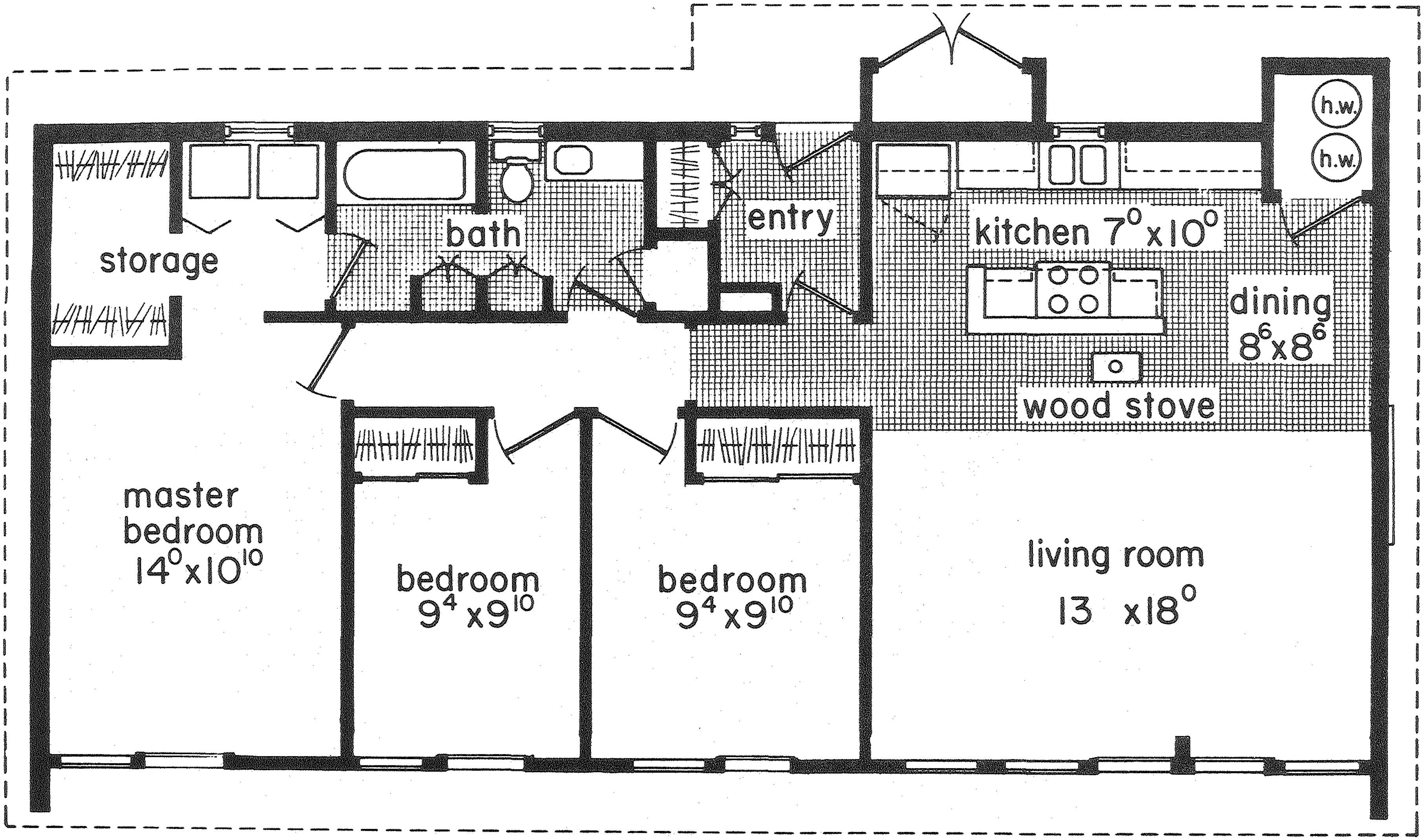

Fig. A1-1: Floor Plan of Prototype Residence

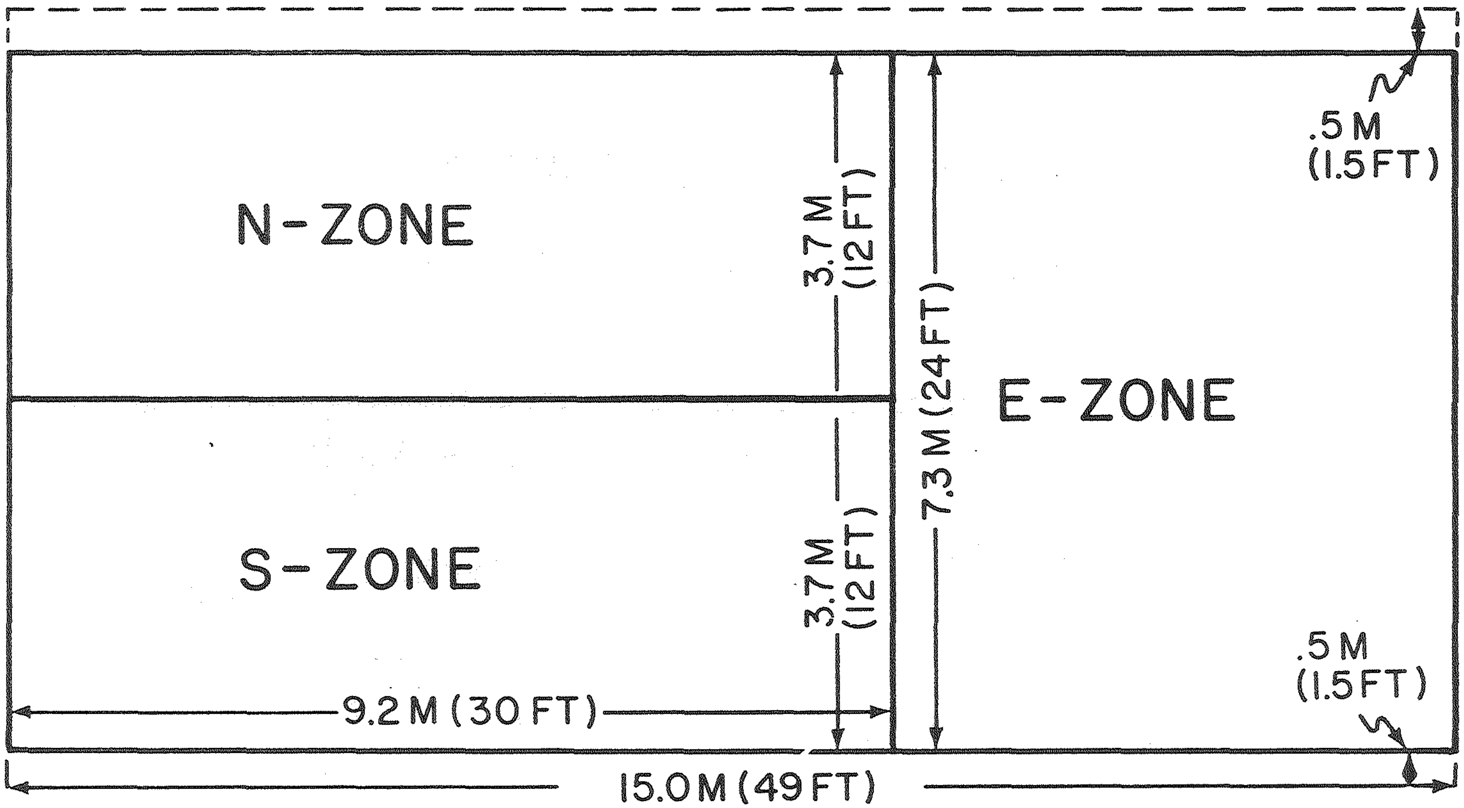

Fig. A1-2: Floor Plan:

Thermal Zones for BLAST Simulation

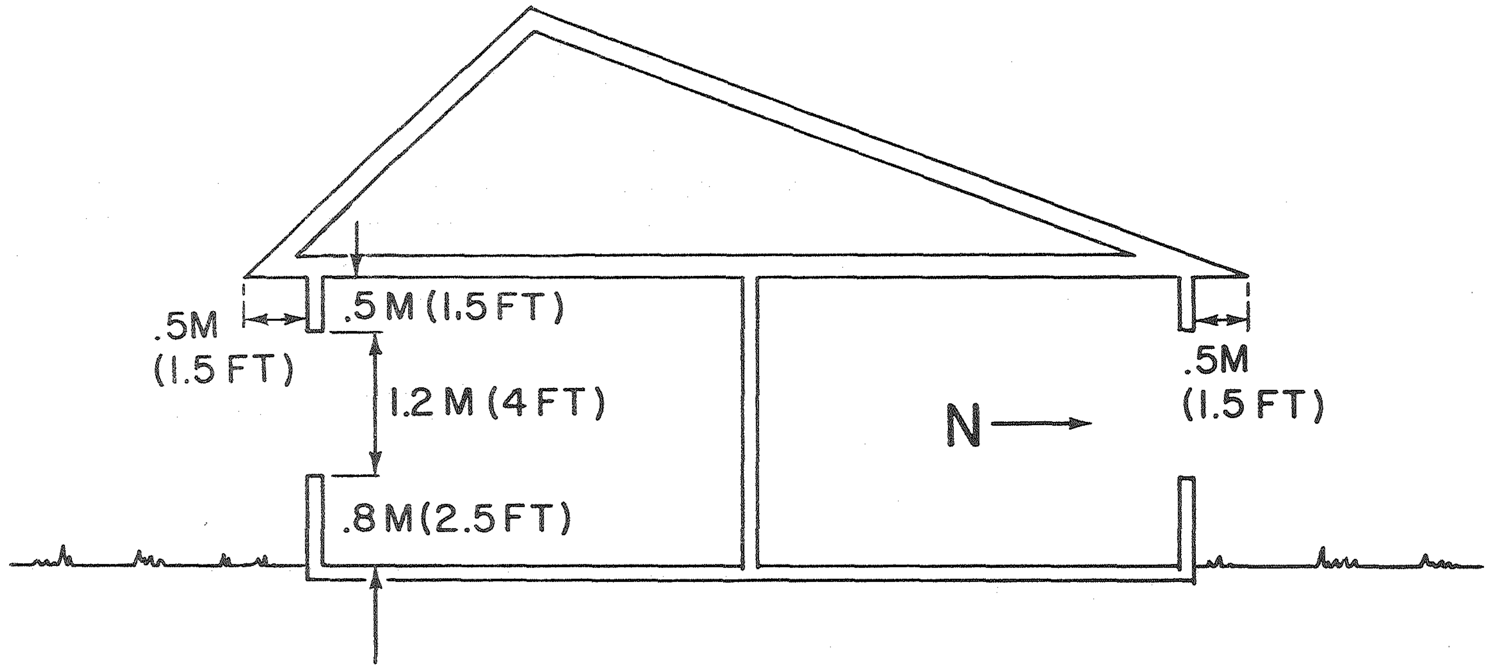

Fig.A1–3: Cross Section

Thermal Zones for BLAST Simulations

plan and section in Figs. A1-2 and A1-3. For the baseline prototype, the Trombe wall used in the TVA design was replaced with glazing equally distributed on the four faces of the building. The structure is rectangular in shape (49 x 24 ft) and has a floor area of 1176 ft^2. The glazed area is 176 ft^2 (15% of the floor area).

The wall and ceiling insulation levels have been chosen to be consistent with the proposed thermal integrity requirements resulting from the Building Energy Performance Standards (BEPS) optimization studies [A1-4]. Double glazing was chosen to be consistent with the TVA and Hastings designs; the BEPS studies have indicated that triple glazing is only marginally cost effective for current construction in most U.S. climates. Internally generated thermal loads are consistent with the Hastings and BEPS assumptions and infiltration rates are consistent with the BEPS studies.

Thermal Model

The thermal model of the prototype employs an unconditioned attic zone above three conditioned zones. Referring to Figure A-1, the zones are identified by function as follows, based on the modified TVA design:

- zone 1: Unconditioned attic above the three conditioned zones.
- zone 2: Kitchen, Living-Dining area.
- zone 3: Bedrooms.
- zone 4: Bath, Hall, Entry, Closets.

Plan and elevation views of the thermal model are shown in Figures A1-2 and A1-3, respectively.

The model uses an insulated slab-on-grade floor and unconditioned attic. Details of assumed materials, constructions, internal loads, infiltration rates, and temperature controls are described below.

(i) Materials: The thermophysical properties of the materials used in the model came from various sources (BEPS [A1-4], ASHRAE [A1-5]).

(ii) Constructions: The materials were subsequently used to form envelope sections. Nominal descriptions of the various constructions follow:

- Walls: The baseline case consists of nominal 2 x 6 frame-cavity walls with 1/2-inch gypsum board, R-19 insulation, insulated sheathing, and wood siding. The stud section of the wall and the insulated cavity section of the wall are treated separately.
- Floor: Four-inch concrete slab-on-grade is assumed over two

inches of R-10 insulation. Half the floor is carpeted.

- Ceiling: A gypsum board ceiling with nominal R-38 insulation separates the occupied space from the attic.

- Windows: The baseline case consists of double glazing. Window areas are consistent with BEPS assumptions. For each zone and external wall, separate windows are aggregated into one, preserving shading relationships.

- Partitions: Gypsum board cavity walls are standard, although both double thickness gypsum board and concrete are options for the construction.

(iii) Furniture: The mass of furniture is not accounted for directly. However, when using BLAST to analyze the building, the effect of furniture on sunlight absorption and instantaneous convective release into the conditioned space is mimicked by a partially absorptive shade inside the windows.

Building Use Parameters

The major parameters associated with construction quality and occupancy of the building are described below:

(i) Temperature Schedules: Interior temperature in the occupied space is maintained in the range from 70 ^{o}F to 78 ^{o}F (BEPS consistent). Heating loads occur when the lower limit must be maintained by the auxiliary system and cooling loads occur to maintain the upper limit. The interior temperature is allowed to float between those limits without causing any load. The control strategy incorporates night setback to 60 ^{o}F from 11 to 7 a.m. The attic temperature is allowed to float totally unconstrained.

(ii) Internal Loads: Internal loads are aggregated within each zone and are compatible with BEPS in the daily totals, although the hourly profiles differ slightly. The total daily load of 15.6 kwh (53,100 Btu) have been allocated rationally between the three zones of the structure on an hourly basis. They include the effects of 2.2 occupants and of appliances and equipment typically found in homes. The resulting internal load profile for each zone is assumed to be the same for all days.

(iii) Infiltration: The dependence of infiltration rates on wind speed and inside/outside temperature difference is consistent with the Achenbach-Coblentz equation [A1-6]. The coefficients in the equation have been adjusted to produce annual average air change rates of 0.6 air changes in the occupied zones and 2.0 air changes in the attic, for a "typical" U.S. climate which is taken to be Washington, DC. The same coefficients are used for all climates, which means that annual average infiltration rates will vary from one climate to another in response to local temperatures and wind speeds.

(iv) Ventilation: Ventilation is used for cooling only when immediate ventilation (opening windows) can eliminate the cooling load.

Thermal Behavior

As a benchmark, the baseline prototype has been simulated in three climates using BLAST. The analyses were driven using TMY weather data. Table A1-I summarizes monthly and annual cooling loads for Madison, Miami, and Nashville.

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A1-6 "Field Measurements of Air infiltration In Ten Electrically-Heated Houses, "C.W. Coblentz, P.R. Achenbach, Trans. ASHRAE, 69, 358-365, 1963.

TABLE A1-I	MONTHLY AND ANNUAL LOADS (KBtu)					
	Madison		Nashville		Miami	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
January	8717	0	3461	0	44	965
February	5691	0	2338	0	44	587
March	4557	0	1462	0	0	827
April	1529	14	401	93	0	838
May	345	224	45	405	0	2330
June	7	524	0	1675	0	3584
July	0	917	0	3100	0	4058
August	0	797	0	2952	0	4267
September	23	191	0	1740	0	4510
October	439	11	155	399	0	3301
November	3458	0	902	0	0	1651
December	5868	0	2903	0	42	601
Annual	30635	2678	11666	10364	130	27528
$Btu/ft^2.yr$	26050	2277	9920	8813	111	23408

APPENDIX 2

BLAST

Introduction

The purpose of this appendix is to provide a brief overview of the public domain building energy analysis computer program BLAST, especially as it relates to the analysis of buildings which incorporate passive solar design features. The program has advanced from its original form, released in 1978 to the current version 3.0. It is fully documented for the user [A2-1,2,3,4] and is available on computer service bureau main frame computers and at several research institutions. The program was written and is maintained by the Construction Engineering Research Laboratory (CERL) and consists of five major in-line subprograms:

- input processor;
- building heating and cooling load calculation routines;
- air handling system simulation routines;
- central energy plant simulation routines; and
- economic analysis routines.

In addition, the BLAST program includes libraries of commonly used data and information and two off line processors:

- a weather data preprocessor which converts standard format weather tapes such as Typical Meteorological Year (TMY) and Test Reference Year (TRY) to BLAST compatible files; and
- a postprocessor report generator which outputs user selected quantities computed during the simulation.

The presence of the mechanical systems and central plant simulation capabilities permits the program to provide total energy analysis capabilities for nonresidential building types. It is similarly effective for analysis of residential scale structures.

Calculation Sequence

Given user defined building parameters, including the architectural configuration, building use characteristics, and heating and cooling system descriptions, BLAST first performs hourly computations of the basic building load including the effects of (1) environmental interactions such as solar gains, conductive heat transfer, and infiltration, and (2) internally generated thermal loads such as occupancy, gas equipment, electric equipment, and lights. The loads are calculated under user defined parameters relating to thermostat control and schedules. The simulation is driven by hourly weather data either from files created by the weather data preprocessor or from design day profiles created as part of the load simulation. In this latter case, the user specifies the extreme in dry bulb and wet bulb ambient temperature, wind speed and clearness for solar radiation; the program then generates the hourly data used in the analysis and performs the load calculation in the same manner that would be used if a weather tape were available. The subprogram which calculates loads generates an output file containing the hourly load components which are read by the air handling systems simulation program.

The secondary system simulation allows the user to select the air handling system type and the specific thermal parameters for components in that system such as terminal reheaters, fans, blowers, hot and cold deck, etc. This portion of the program calculates the hourly secondary energy requirements which will meet the building loads under the constraints imposed by the design of conventional systems, including outside ventilation air, latent loads, distribution energy, and component efficiencies.

The output of the mechanical system simulation program is a file of loads imposed on the primary equipment in the central plant where the operation of boilers, chillers, cooling towers, etc., are simulated. Given the operational parameter of the plant components, the input fuel requirements to meet the demands of the secondary system are calculated. The fuel input is then used in the economic analysis.

Characteristics

The major characteristics of each subprogram are outlined below:

(i) Input Processor: User communication with BLAST is through a structured English language syntax processor developed specifically to simplify input [A2-1]. The user specifies names for materials and defines them in terms of thermophysical properties. Constructions are then defined as combinations of defined materials. Similarly, control strategies, internal load profiles, secondary and primary equipment components, and other design parameters are given names and defined in terms of elemental parameters.

Given the constructions, building use parameters and equipment specifications, the user defines the geometry and mechanical systems on a zone-by-zone basis, coupling the zones as appropriate and including the internal load and system information. The user initiates the simulation by coupling the building description input to a weather file.

(ii) Loads Calculation: In the computation of zone and building loads, BLAST-3.0 uses a thermal balance method, the specifics of which were developed by CERL, which represents the state of the art for thermal load calculations [A2-5]. For each hour of the simulation, energy balance equations are set up for each internal surface of the building defined by the user and for the air in each zone of the structure; these equations are solved simultaneously using iterative techniques. The individual equations include the dynamic thermal excitations for the surface that they represent and the equations are coupled. The energy balances include:

- radiative excitations of the surfaces due to solar absorption and to conventional thermal sources such as occupants, equipment, lighting, baseboard heating, and other zone surfaces;
- convective excitations of the zone air resulting from infiltration and ventilation and from thermal couplings to the surfaces defining the zone, air handling equipment, baseboard heating equipment, occupants, lighting and other equipment; and
- conductive excitations through the construction which define the surfaces of the individual zones.

The simultaneous solution of the energy balance equations produces the zone loads directly in terms of the baseboard energy input and the convective input from the air handler.

(iii) System Simulation: The air handling system is defined by the user in terms of system type (e.g., VAV, multizone, etc.) and system component performance (e.g., fan coil unit parameter, air supply, etc.).

(iv) Central Plant Simulation: Available central plant equipment and specifications are identified by the user (boilers, chillers, cooling towers, etc.).

<u>Passive Analysis Capabilities</u>

The current version of the program, BLAST-3.0, incorporates several new features important to the energy analysis performed in this study. These features are described below:

(i) Multizone analysis: The program calculates the thermal loads and air temperatures simultaneously for up to twenty thermal zones within a single building. The conductive, convective, and radiative excitations in each zone and the conductive and convective coupling between zones are fully accounted for.

(ii) Nonlinear Internal Thermal Couplings: The iterative thermal balance allows load calculations which include nonlinear coupling between the room air and elements of the building and between different building elements. This permits thermal radiation to be dealt with more exactly than past thermal balance techniques and obviates the assumption that the convective couplings between zone surfaces and zone air are constant.

(iii) External Surface Thermal Balance: A detailed thermal balance is performed on each external surface of the building in order to calculate the external surface temperature which is conductively coupled to the interior surface. The outside surface balance includes solar absorption, nonlinear convective coupling to ambient air, and radiative coupling to the sky and to the surrounding terrain.

(iv) Shading Devices: The program computes the solar gain incident on all external surfaces on an hourly basis, properly accounting for the dynamic effects of a full range of arbitrarily shaped, attached shading devices such as overhangs, fins, and reveals. Detached shading devices such as adjacent buildings can also be described. Finally, either attached or detached shading devices can be given a solar transmission and can be seasonally scheduled so that, for example, user control of awnings and/or the shading effects of deciduous trees can be represented.

(v) Direct Solar Gain: the user specifies the glazing type, transmission at normal incidence and indicates whether a thin reflective film is present; BLAST calculates the transmission, absorptance, and reflectance of fenestration systems on an hourly basis from first principles. Hourly internal solar gains are then allocated to each internal surface based on the user specified optical properties of the finish materials, the geometric relationship between the individual windows and all of the internal surfaces. This allows accurate representation of the relative effects of various internal thermal mass configurations.

(vi) Thermal Mass: Since the user defines the specific geometry and construction of individual surfaces defining the zones in a building, the mass configuration is entirely specified as an integral part of the building description. Thermal conduction in massive building materials is analyzed using conduction transfer functions, thereby accounting for thermal storage as well.

(vii) Thermostat Control: Auxiliary heating and cooling equipment are coupled to the load calculation through hourly and seasonal thermostat control profiles for each zone in the structure. The user can specify the temperature sensed by the thermostat as an arbitrarily weighted average of true air temperature and true mean radiant temperature.

(viii) Unconditioned Zones: By neglecting to specify heating and cooling system controls for a specific zone, the thermal behavior of that zone will be simulated with a fully floating air temperature. In this way, sunspaces, atria and other buffer spaces can be analyzed.

(ix) Ventilation Cooling: In addition to standard economizer operation in the mechanical system simulation subprogram, the user can specify separate forced direct ventilation cooling of each zone. This feature allows simulation of night flushing of a structure or controlled flushing of excessive thermal gains independent of the conventional HVAC system operation.

The passive analysis capabilities described above are in addition to the standard analysis capabilities of the program. They allow thorough analysis of the energy consumption implications of a variety of passive design options as well as standard building configurations.

Verification Summary

Two BLAST verification studies have been completed to date. In the first [A2-6], BLAST predictions for temperature profiles were compared to measurements performed in an unconditioned thermally massive direct solar gain test cell located at Los Alamos National Laboratory. Comparisons were made for data collected during three different climatic seasons. To within uncertainties in the measurements, quantitatively acceptable agreement was obtained in all cases. This verification provides credence to the solar transmission, solar gain and conductive loss calculations performed by BLAST.

The second verification utilized data collected in a massive full scale structure located in an environmental chamber at the National Bureau of Standards [A2-7]. No solar gains are included in the chamber and the building is temperature controlled by a monitored cooling coil. The test structure is excited by the imposition of a controlled 24 hour outside temperature profile. This verification therefore complements that from the test cell in that it included comparisons of measured and computed thermal loads. In addition, the data from this test includes measured air temperature profiles under conditions when ventilation cooling of the structure is provided at night when the outside air temperature is below the comfort range. In both of these verifications, quantitatively good comparisons were obtained [A2-8].

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